OKLAHOMA RESEARCH PROGRAM
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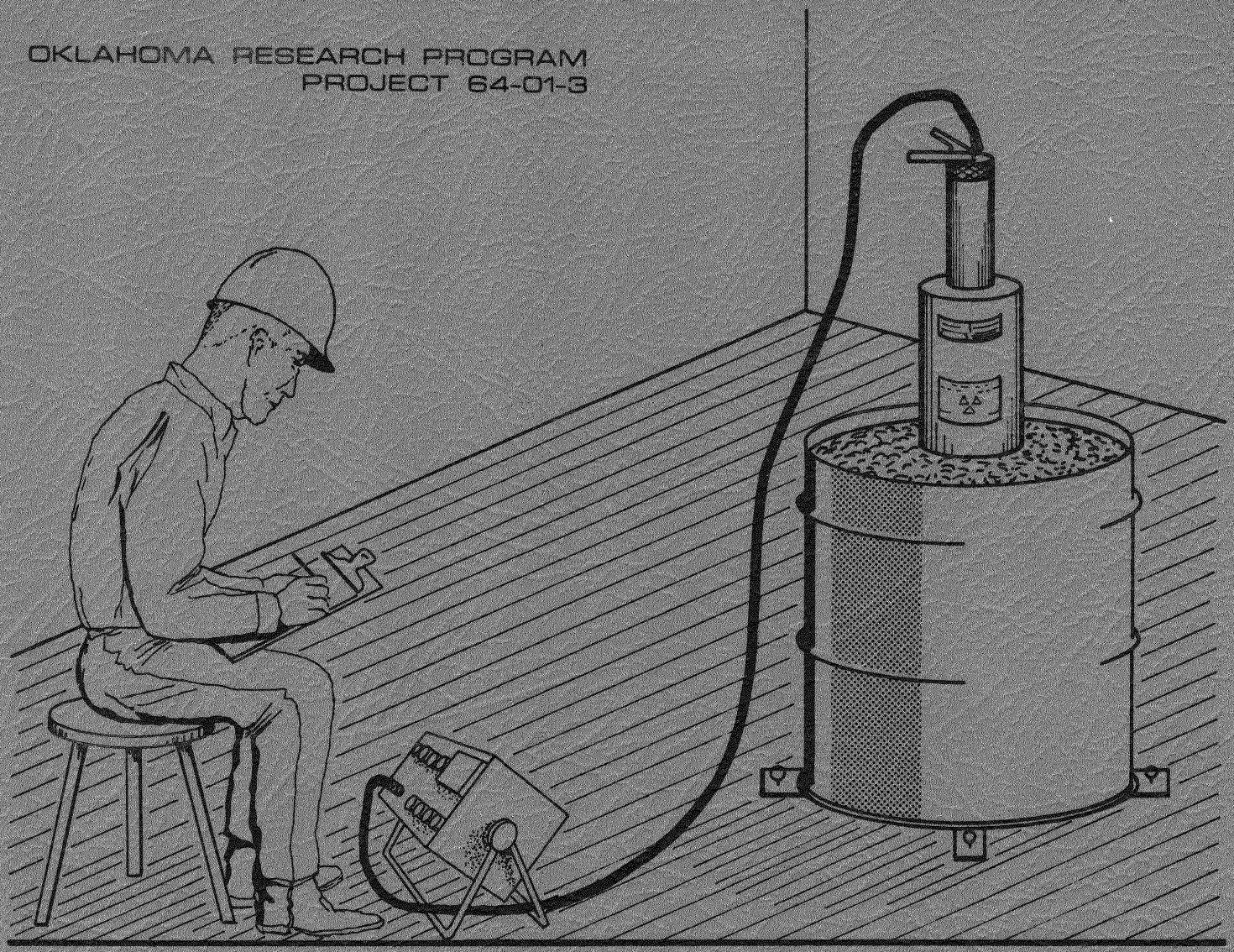

SUBGRADE MOISTURE VARIATIONS

INTERIM REPORT IV

SUGGESTED NUCLEAR DEPTH GAGE CALIBRATION PROCEDURES

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INTERIM REPORT IV: SUGGESTED NUCLEAR DEPTH GAGE CALIBRATION PROCEDURES

by

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PREFACE

Moisture variation and accumulation under highway pavements often lead to premature pavement failure. Measurement of subgrade moisture changes and correlation of these data with soil, climate, and pavement conditions may yield information useful in improving pavement performance.

Nuclear depth moisture and density gages offer an efficient means of measuring long-term subsurface moisture changes, if correctly calibrated. This report describes calibration of nuclear depth gages for project use. The procedure described herein is not proposed as an overall solution to the nuclear depth gage calibration problem. For the present, each particular type of user will have to decide which technique best suits their own work. However, the procedure described in this report, while more empirical than scientific at this stage, appears to offer an efficient and practical means of calibration for the range of measurement useful in soils/highway engineering.

This report is the fourth of an interim nature to be submitted by the Subgrade Moisture Variations research project, Oklahoma Research Program Number 64-01-3. Future interim reports will describe data collected to date and preliminary evaluation of these data.

Support for this study is provided by the State of Oklahoma, Department of Highways, in cooperation with the U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads. This support is gratefully acknowledged.

R.K.M.

T.A.H.

LIST OF REPORTS

Interim Report I: "Preliminary Planning," by T. Allan Haliburton, June, 1966, reviews current utilization of nuclear equipment and presents a tentative plan for project operations.

Interim Report II: "Access Tube Installation," by Wayne L. Heiliger and T. Allan Haliburton, January, 1967, describes procedures used to install access tubing for nuclear depth moisture-density equipment beneath highway pavements.

Interim Report III: "A Preliminary Standardization and Calibration Procedure for Nuclear Depth Moisture/Density Gages," by E. W. LeFevre and Phillip G. Manke, May, 1967, describes an interim calibration procedure for project use of nuclear depth moisture and density gages.

ABSTRACT

An experimental procedure for calibration of nuclear depth moisture and density gages is described. Calibration of the gages was accomplished utilizing laboratory standards constructed of native Oklahoma soils. The soil standards were compacted to a known density and moisture content; one sand and two cohesive soils were employed. Calibration curves were derived by comparing instrument response with probes in the standards to the various densities and moisture contents of the standards. Previous work in the calibration area was reviewed and the effect of soil type on gage response was investigated.

A satisfactory method of constructing laboratory standards was developed. The calibration curves for the gages indicated that soil type influences instrument response. Each soil had a separate and unique calibration curve for moisture content and for density. The use of dual-purpose standards, to calibrate both moisture and density gages, was proven desirable. Specific calibration curves are recommended for project use.

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CHAPTER 1. INTRODUCTION

"Highway pavement is only as good as its subgrade" -- this old cliche is quite true. Subgrade soils are definitely important in highway design and construction, thus any factor which alters engineering properties of the subgrade is of critical concern to the highway engineer. Moisture variation and accumulation can greatly weaken the subgrade by causing changes in soil volume and strength. Measurement of subgrade moisture conditions and subsequent correlation of these data with soil, climate, and pavement conditions may allow development of revised design procedures to improve pavement performance.

Accordingly, the School of Civil Engineering at Oklahoma State University, in cooperation with the Oklahoma Department of Highways and the Bureau of Public Roads, USDT, initiated, in June, 1964, a six-year study of subgrade moisture variations under Oklahoma highway pavements (Ref 1). Fifty field test sites have been installed to date in northeastern and north central Oklahoma, during the summers of 1966 and 1967 (Ref 2). Nuclear depth moisture and density gages were chosen to measure subgrade soil conditions. These gages allow nondestructive in-situ soil density and moisture content measurements.

Statement of the Problem

The use of depth density and depth moisture probes for rapid non-destructive soil testing (density and moisture content determinations) has been investigated since 1950. A primary obstacle hindering

their acceptance as a standard test procedure is calibration of the equipment. Calibration of an instrument of this type usually refers to the development of an empirical, graphical relationship between apparatus response and soil conditions. Reliability of field measurements using nuclear depth probes is dependent on calibration accuracy.

Much of the difficulty can be traced to the character of soil itself. Soil types may vary widely in a given area. The physical, chemical, and mineralogical characteristics of soil are subject to variation. Field measurements with nuclear depth equipment must be valid for the entire spectrum of subsurface conditions. The feasibility of employing nuclear probes for quality control and inspection is dependent upon their reliability under all field conditions.

Therefore, a calibration procedure using actual soil "standards" would be desirable for nuclear probes. A standard is defined as a mass of soil which has been compacted to a known density at a known moisture content under controlled conditions. Construction of this standard requires an efficient method of soil preparation and placement.

Scope of this Report

A method of calibration standard construction using three Oklahoma soils as calibration media is described herein. Thirteen standards were constructed with various densities and moisture contents. The equipment response of nuclear depth density and depth moisture probes is evaluated in terms of empirical calibration curves obtained from the soil standards. The effects of soil type, standard container geometry, and calibration procedure on equipment response are also investigated.

CHAPTER 2. THEORY OF NUCLEAR MEASUREMENT

The basic operational theory behind nuclear testing procedures is of considerable importance to the calibration problem. The processes involved are, in general, quite complicated because of radiation phenomena, but the more important points will be summarized below.

Density Measurements

The density measurement technique utilizes a probe with a radioactive source, usually radium-226, which emits gamma radiation at a constant average rate. Gamma particles are capable of penetrating dense materials but are slowed with an accompanying energy loss as they pass through matter. Some gamma particles may be scattered through the material in a series of collisions, but others may be absorbed.

Gamma particles have three distinct reactions as they strike other atoms. From Fig 2.1, these reactions are the photoelectric effect, the Compton effect, and pair production. If a gamma particle collides with an orbital electron of another atom, it may transfer all of its energy to the electron. The "excited" electron is ejected from the parent atom with less energy than the original gamma ray. Materials have different rates of particle absorption by the photoelectric effect. The probability of this phenomenon occurring in a given material is dependent on the density of the material, atomic number and mass of the element, the percentage composition, and the total number of elements involved.

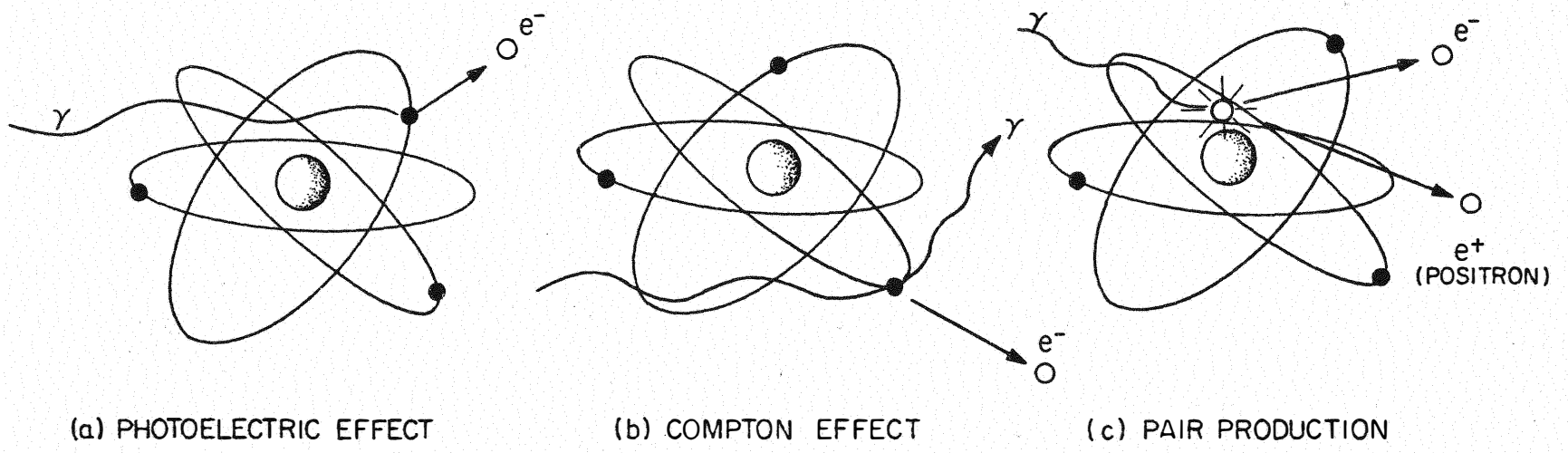


Figure 2.1. Gamma Particle Interaction (After Ref 4)

The Compton effect occurs when gamma particles collide with an orbital electron and are scattered with energy loss in the collision. The gamma particle continues in an altered direction with a lower kinetic energy. Usually, the electron struck is placed in an "excited" state and is ejected from the parent atom as with the photoelectric effect.

The third case is not significant in the mechanics of depth density measurement. Pair production occurs near the nucleus of an atom with a positron and electron being produced.

Photoelectric effects are predominant in soil materials when gamma particles have energies less than one Mev (million electron volts). One electron volt is the energy gained by an electron in falling through a potential difference of one volt. The Compton effect occurs as the principle mode of gamma particle interaction in the range of energies between one-half Mev to four Mev.

Two methods of gamma particle detection are used in conjunction with density testing. The backscatter process counts the number of gamma particles which are deflected by the soil back toward the source. The direct transmission technique utilizes gamma particles which pass through the soil with very little deflection. The source is at one location and the detection tube at another. A depth density probe employs the backscatter technique.

The density probe, seen in Fig 2.2, has two principle components, a radium-226 source at the bottom and a Geiger-Mueller tube at the top. The G-M tube consists of a thin cylindrical shell (the cathode) and a fine wire anode suspended in an inert gas. A voltage of slightly less than that required to produce a discharge in the gas is applied between

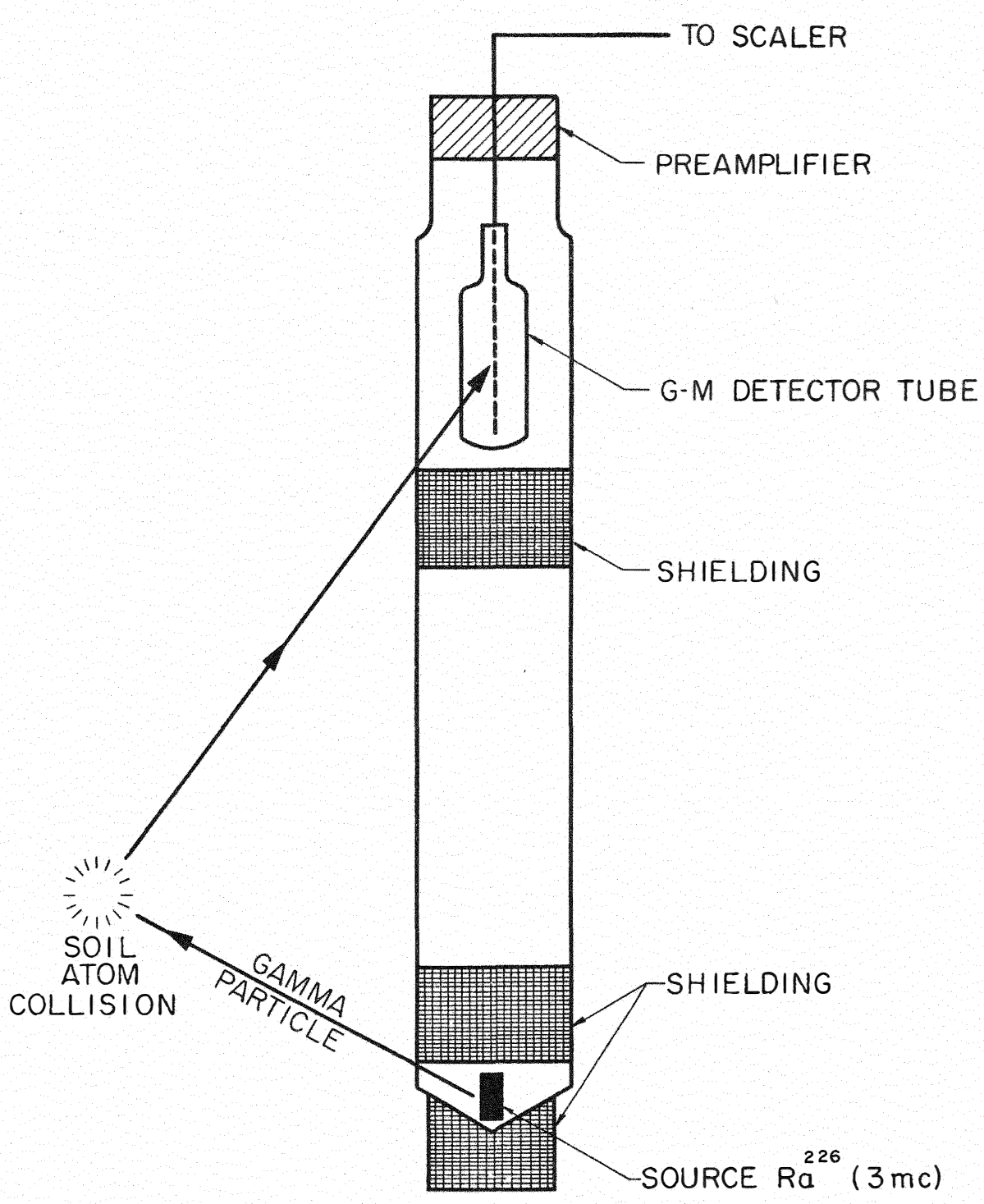


Figure 2.2. Depth Density Probe

the anode and cathode. When a gamma particle enters the tube its energy ionizes a gas molecule. The electrons produced by ionization are accelerated toward the anode by the voltage gradient and cause additional ions to be produced. This is an extremely rapid reaction and produces an electrical discharge in the gas, resulting in an electrical impulse to the external circuit. The detection system counts all gamma particles regardless of their energy level. Shielding is placed between the detector and the source to prevent direct transmission. The distance between source and detector tube is most important because the probability of backscattered gamma radiation reaching the G-M tube increases with distance. The sensitivity of this instrument is quite poor, but it is believed that reliable results can be obtained when used with accurate calibration data (Ref 3).

As a soil increases in density, its ability to absorb gamma particles also increases. Fewer gamma particles will be backscattered to the detector tube. This means that a soil of 150 pcf wet density will have an instrument response or pulse count lower than a soil with a 120 pcf wet density. This relationship is valid for densities encountered in highway subgrades. The density measured is the total mass or wet density of the material.

Moisture Measurements

The nuclear method of determining moisture content employs fast neutrons. The moisture probe used in this study, shown in Fig 2.3, depends on a radium-beryllium reaction to produce fast neutrons. The radium-226 emits alpha particles which collide with the beryllium. This collision releases fast neutrons to be transmitted into the soil.

Neutron interaction with matter is quite similar to that dis-

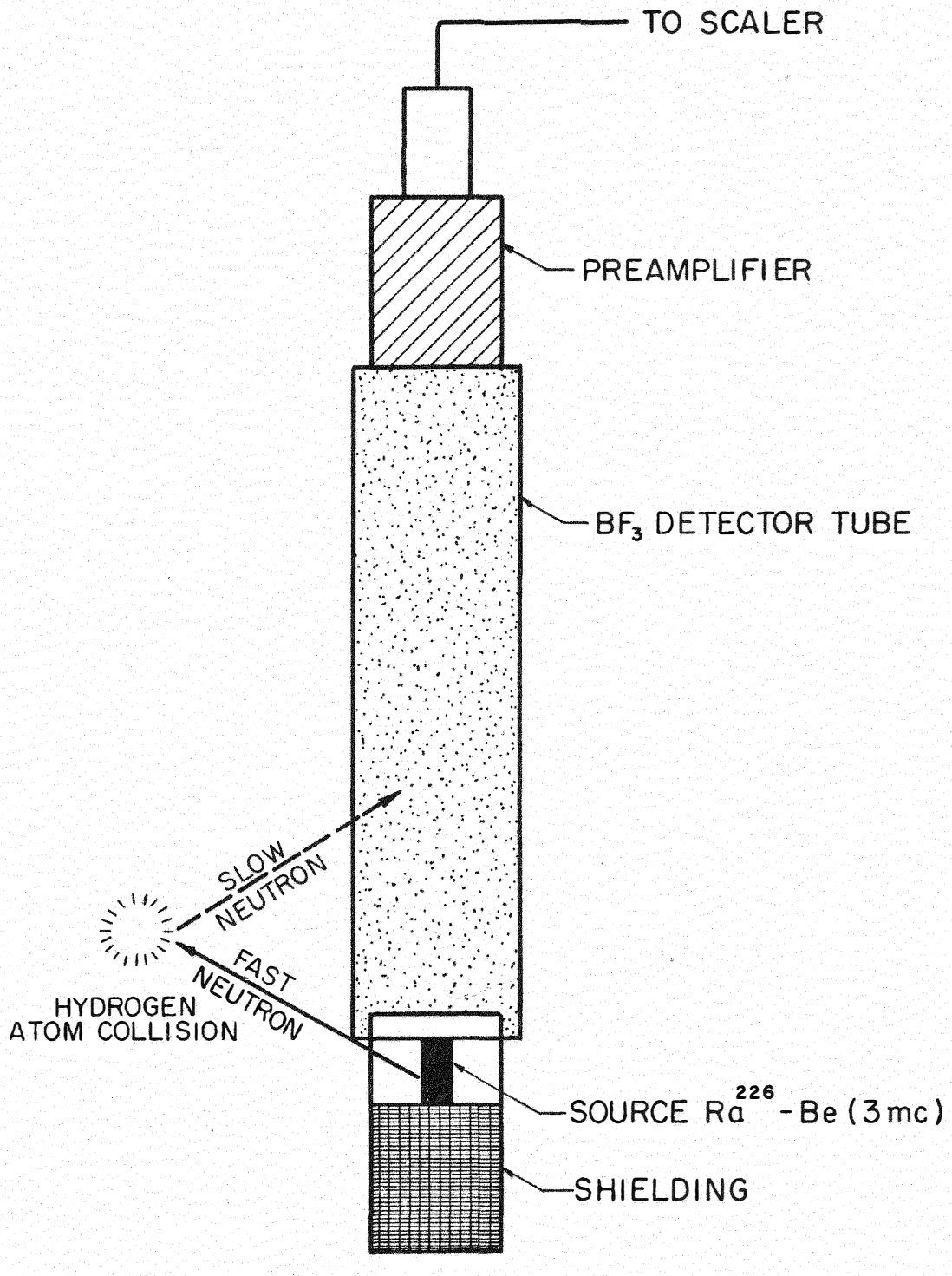


Figure 2.3. Depth Moisture Probe

cussed for gamma radiation. The neutron may engage in an elastic collision with other nuclei in the soil, or it may be absorbed by a nucleus. This results in the annilation of the neutron and, subsequently, an "excited" atom.

In any elastic collision the colliding particles must not lose their total kinetic energy. However, particle velocity may be altered. If an impinging neutron strikes a particle of the same mass in an elastic collision, the neutron could impart some or all of its energy to the struck particle. However, if the neutron were to strike an atom of much larger mass, it would merely be deflected with little loss in kinetic energy. The probability of an elastic collision is dependent on the size and mass of the atomic nuclei involved.

The only particle which has a mass of similar size as the neutron is the hydrogen ion. Therefore, hydrogen would have a greater probability of slowing the fast neutron. As can be seen in Table 2.1, it takes only about eighteen collisions with hydrogen atoms to slow or "thermalize" a fast neutron. Lithium is next, but it required approximately four times the number of collisions to thermalize a neutron. Furthermore, lithium is not found abundantly in most soils. Hydrogen exists as water and also in the ionic state. It can be said that the moisture probe is a hydrogen sensitive device, and by this means gives an indication of the amount of water in the soil.

The other important neutron interaction mode is absorption. The ability of an atom's nucleus to capture a neutron is a function of the element and neutron energy. A list of strong absorbers or "poisons" is included in Table 2.2. The best absorbers have absorption cross-sections which are quite high. The unit of measurement for this property is the

Element	Average number of collisions required for thermalization	Element	Average number of collisions required for thermalization
Hydrogen	18.2	Silicon	262
Lithium	69.3	Phosphorus	288
Beryllium	88.1	Sulfur	298
Boron	104.5	Chlorine	329
Carbon	115.4	Potassium	362
Nitrogen	133.5	Calcium	371
Oxygen	152	Titanium	442
Sodium	215	Manganese	514
Magnesium	227	Cadmium	1028

TABLE 2.1. Relative Effectiveness of Some Elements in Slowing Down Fast Neutrons

Some strong absorbers		Area Barns	Elements commonly encountered	Area Barns
Rare Earths	to	46,000	Iron	2.53
Cadmium		2,450	Potassium	2.07
Boron		755	Nitrogen	1.88
Indium		196	Sodium	0.505
Gold		98.8	Calcium	0.44
Lithium		71.0	Hydrogen	0.332
Silver		63.0	Aluminum	0.230
Chlorine		33.6	Magnesium	0.063
			Carbon	0.0034
			Sulfur	0.00052
			Oxygen	0.0002
			Phosphorus	0.0002
			Silicon	0.00016

TABLE 2.2. Relative Absorption Capacity of Some Elements for Thermal Neutrons (0.025 ev)

Barn; it is equal to an area of 10^{-24} cm^2. Although these neutron cross-sections have area units, they are not the physical cross-sections of the nuclei. In fact, nuclides have several cross-sections, and these variable cross-sections are often complicated functions of neutron energy (Ref 4).

Slow neutrons are counted by a tube filled with boron-trifloride gas enriched with boron-10. The slow neutrons combine with the nuclei of boron-10 to form boron-11. This element is quite unstable, and emits alpha particles when it disintegrates. These alpha particles ionize the gas in the detector tube to produce electrical pulses which are counted.

Certain of the neutron poisons (boron, cadmium, chlorine, and iron) will produce undesirable effects since the slow neutrons counted do not give a valid indication of soil hydrogen content. For instance, boron in concentrations of 2 to 100 ppm will give errors in equipment response up to ten per cent. A similar deviation will occur in the slope of the calibration curve with a chlorine content change of .0122 gram/gram of dry soil. An iron content change of five per cent will alter the slope of a moisture calibration curve by 3.3 per cent (Ref 5). Also, soils with high organic content (for example, peat) will give inaccurate results because of the presence of organic compounds. The hydrogen in these sources will thermalize neutrons just as efficiently as hydrogen in water.

CHAPTER 3. REVIEW OF PREVIOUS CALIBRATION PROCEDURES

Nuclear equipment employed in this study was manufactured by Troxler Electronic Laboratories, Inc., of Raleigh, North Carolina. They rely on non-soil materials to produce factory calibration curves for nuclear depth density and moisture probes. Portland cement concrete was chosen as the density calibration media. Modified fifty-five gallon oil drums were filled with concrete, vibrated to uniform densities and moist cured. Aluminum access tubing was placed in the barrel prior to pouring of the concrete. The surface of the cured material was coated with epoxy to prohibit moisture fluctuations (Ref 6).

The moisture equipment was calibrated with cadmium chloride-water solution standards. Cadmium is a very efficient absorber of fast neutrons; a high cadmium content will produce a low return of thermalized neutrons to the detector tube. The water acts as a thermalizer of fast neutrons. Various cadmium chloride-water solutions were correlated to soil response at a known moisture content; soils native to the North Carolina region were employed in this correlation (Ref 6).

Some early studies theorized that calibration curves between moisture content and counting rate would be independent of soil type. Belcher, Cuykendall and Sack first arrived at this conclusion (Refs 7, 8). The U.S. Army Corps of Engineers calibrated nuclear depth probes with laboratory standards (Ref 9). This calibration was checked in the field by comparing gravimetric moisture contents of soil samples obtained at test sites to the moisture content indicated by equipment

response. It was observed that separate curves could be fitted through the data more closely than a single curve. However, the study chose to develop a single curve from the data obtained for density and moisture respectively. The Corps of Engineers concluded that this procedure had too much experimental error. They also state the density probe was not accurate enough for airfield measurements because of the calibration problem, but the moisture probe might be.

Later research by Belcher, Cuykendall, Sack, and Carlton (Ref 10) invalidated earlier work and recommended separate curves be developed for density gages. They found that composition or soil type effects were as much as nine per cent, indicating the need for separate calibration curves.

Holmes and Jenkinson (Ref 11) have stated that the character of the absorption cross-section of soil solids and the possibility of hydrogen existing within a soil in compounds other than water complicate the single curve theory.

LeFevre and Manke (Ref 3) though acknowledging that separate curves for individual soils did exist, attempted to develop a median calibration curve for moisture and density gages. They state that for practical purposes the single curve approach is warranted so this method may be considered feasible for engineering use.

Richards (Ref 5) attempted density calibration using drums filled with uniform sand. Moisture studies utilized the same material with various amounts of water added. The sand was compacted in six inch lifts with a hand tamp. Pulse count in the various standards was correlated to moisture content as determined by samples taken from the standards. Cohesive soils were not employed due to problems of mixing

and placement. The curve produced in the laboratory was compared to field data. Moisture readings were collected from several sites and in various soil types. The counts were used in conjunction with the laboratory curve to predict in-situ moisture content. Soil samples were removed from each soil test site, and gravimetric moisture determinations were completed as a check on the validity of the calibration curve. Richards concluded that this approach to the problem proved unsuccessful as unsatisfactory results were obtained.

Since preparing soil standards involved much time, labor, and large volumes of soil, Van Bavel, Nielson, and Davidson (Ref 12) chose neutron absorbers as calibration media. Their research concluded that neutron counts similar to those in soils could be obtained. Furthermore, they state that any field calibration will give results of indecisive validity.

McHenry (Ref 13) and Ballard and Gardner (Ref 14) recommend that standards must conform to certain basic criteria. They mention such factors as cheap construction, use of readily available materials, and use of materials which will not undergo extensive changes over a long period of time. The standard should provide a wide range of readings for the nuclear equipment. Other investigators have done work with paraffin, sand and ammonia alum mixtures, and polyethylene materials as calibration media (Ref 13). Ballard and Gardner (Ref 14) suggest possible standards of aqueous solutions of salts, slurries, non-compactible powders, solids, or sized solid particles. They also present some work with a mathematical analysis of the gamma scattering process and neutron interaction in a mass model.

LeFevre and Manke (Ref 3) used limestone aggregate, river gravel,

expanded shale, and Permian red clay as soil standards. The aggregate, gravel, and shale were tested in dry, saturated, and drained states. Both density and moisture calibration curves were developed from this set of standards. The cohesive soil, Permain red clay, was mixed to various water contents and compacted in modified barrels by a power tamp.

Relatively small confined masses of material used as calibration standards are limitations in themselves. The moisture probe has a sphere of influence which varies with the moisture content. Van Bavel (Ref 15) has determined that this zone around the probe can be expressed by the following equation:

$$R \text{ (inches)} = 5.9 \left(\frac{100}{\text{Vol \% Water}}\right)^{1/3} \qquad (3.1)$$

where R is the radius of a sphere of neutron influence with its center at the source. This relationship is invalid below three per cent of water by volume. Richards (Ref 5) states that the minimum radius is from about four inches in water to over eighteen inches in dry soil. Other investigators have stated that the sphere of influence may vary from twelve to sixteen inches in ordinary soils. Troxler Electronic Laboratories references Van Bavel's equation in its literature on moisture probe operation (Ref 16).

It is necessary to keep the sphere of influence of the moisture probe within the container to get valid results. The container's dimensions directly limit the moisture content to above a critical minimum value. A small container will, therefore, have a high minimum moisture content. In this connection Van Bavel (Ref 12) recommends that for calibration purposes at low moisture content, a homogeneous

soil mass of at least four-foot dimensions is required.

The sphere of influence for the Troxler density probe is approximately five inches (Ref 17). This dimension is not of critical concern in the study as it is well within the boundaries of the calibration standard container.

The previous calibration experiments obviously illustrate the obstacles of equipment calibration. Although non-soil materials give excellent results in some cases, the problems involved with soil still exist. The authors chose to calibrate using soil standards with controlled moisture contents. Artificial standards were not considered. Furthermore, the authors chose cohesive soils as calibration media for two sets of standards. Cohesive soils have been neglected because of mixing and placement problems, but generally they are of critical concern in highway subgrades. Soils with high clay content are quite sensitive to moisture changes. In Oklahoma expansive clays are abundant and are thought to cause many subgrade failures.

It should be noted that this study required calibration of both moisture and density probes. Rational subgrade moisture investigation requires knowledge of engineering moisture content (weight ratio of water to soil solids in a soil mass). Water quantity, in pounds per cubic foot, cannot be related to general soil properties, liquid and plastic limit, shrinkage limit, optimum moisture content, etc. To obtain engineering moisture content, one must subtract the amount of water (pounds per cubic foot) from the wet density to obtain the dry density. The moisture content in pounds per cubic foot is divided by the dry density to determine the engineering moisture content in percent. Therefore, civil engineering requirements put an additional burden on calibration. Both probes must be accurate to produce acceptable data.

CHAPTER 4. CALIBRATION PROCEDURE

Materials

One sand and two cohesive soils were selected for the calibration standards. All materials are found in Oklahoma and represent a general cross-section of soils encountered in the state.

A fine yellow sand was located four miles west of Sapulpa, Oklahoma on highway US 66. As is seen in Fig 4.1, the sand is quite uniform. This material was weathered from a limonitic yellow sandstone formation which outcrops in the immediate area. It was selected because its grain size was between the coarse aggregates used by LeFevre and Manke (Ref 3) and cohesive soils.

Permian red clay (PRC) was selected as the second material because of its abundance in the Stillwater area. Also, LeFevre and Manke used the soil in their preliminary calibration study, and the authors desired to extend their work with the material. This clay was obtained from the excavation of the mathematics and statistics building on the Oklahoma State University campus at a depth of ten feet. Its physical properties can be seen in Fig 4.1 and Table 4.1. Grain size distribution data were obtained by hydrometer analysis.

The third soil was a brown silty clay found southeast of Perry, Oklahoma on highway US 177. This material was selected because it had different characteristics than the Permian clay or sand, i.e., another distinct soil type. Its physical properties, see Table 4.1, indicated it was a good subgrade material; this is unusual in

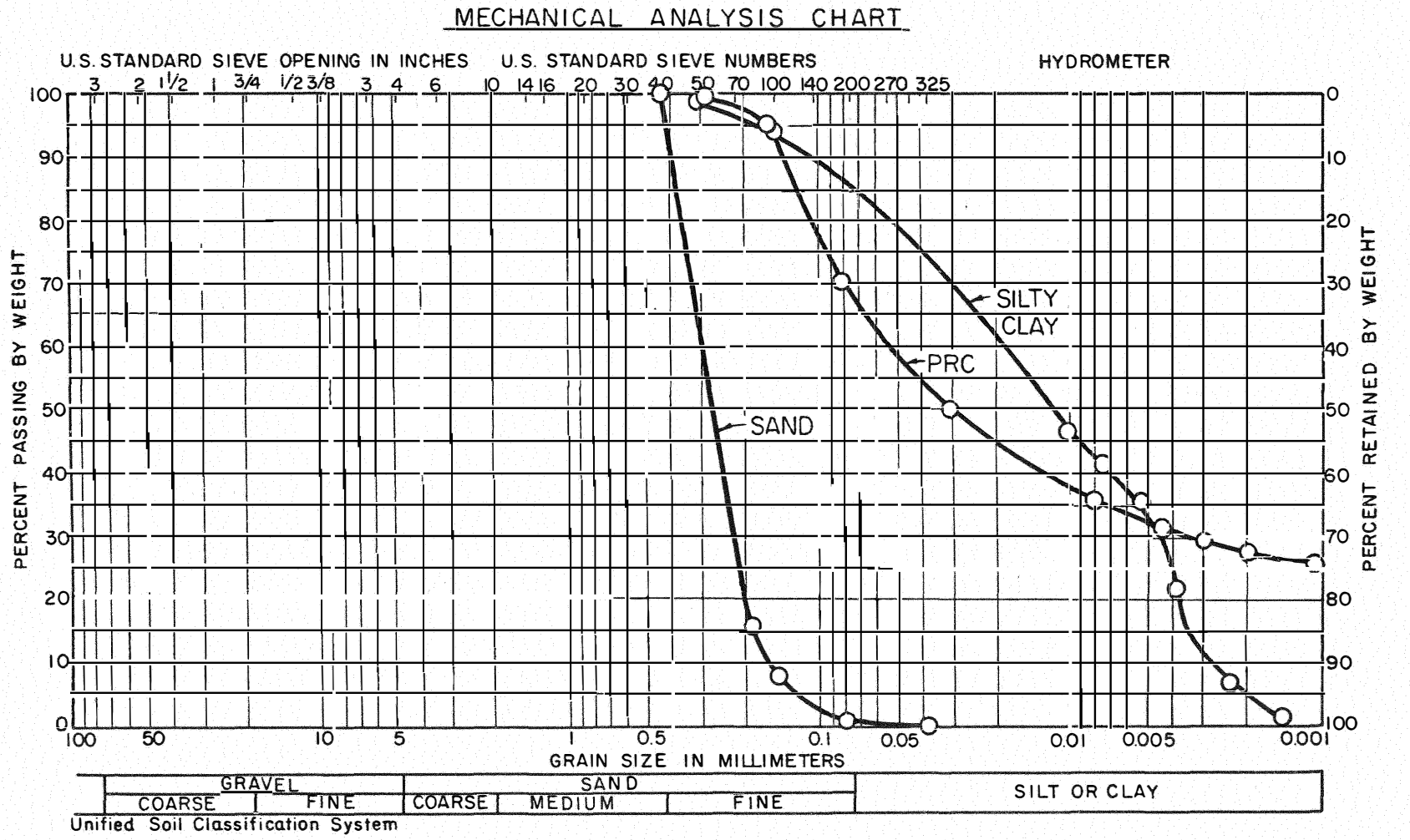


Figure 4.1. Grain Size Distribution of Calibration Soils

Soil	Physical Properties				Lineal* Shrinkage	Classification AASHO--UNIFIED	
	w_L	w_p	I_p	G_s			
Sapulpa Sand	NP	NP	NP	2.66	NP	A3	SP
Permian Red Clay	41.3	22.0	19.4	2.72	11.8	A7	CL
Perry Silty Clay	23.1	18.0	5.1	2.66	5.3	A4	ML

*Texas Highway Department Bar Method

Table 4.1. Physical Properties of Calibration Soils

north central Oklahoma because Permian red clay predominates. The soil deposit was near a small stream and therefore it is believed the silty clay was deposited by water action. A trace of sand was also found in the soil. The grain size data were obtained by hydrometer analysis.

Thus, the selected soils for nuclear probe calibration provided two good and one very poor subgrade material. A grain size range was obtained that included fine sand, silt, and colloidal size clay. With the inclusion of LeFevre and Manke's data on nuclear probe calibration, the entire spectrum of Oklahoma soils would be, to some extent, investigated.

Soil Preparation

The sand was wet sieved through a U.S. Bureau of Standards No. 16 sieve into a thirty gallon waste can. Most of the organic matter (roots, weeds, etc.) was retained on the sieve screen and all of the sand passed into the can. The majority of clay particles found with the sand remained in wash water suspension and were removed as the water overflowed the container. The sieved sand was then oven-dried and placed in G.I. cans for storage.

The cohesive soils were processed differently. The soil was oven-dired for twenty-four hours, see Fig 4.2, and allowed to cool. The dry soil was placed in a Los Angeles Abrasion Test machine, shown in Fig 4.3, and pulverized until the soil passed the U.S. No. 40 sieve in a Gilson Mechanical Testing Screen, shown in Fig 4.4. The PRC has a very high dry strength and it required about one hour for the abrasion machine to break up thirty pounds of soil. Only one third of this material would pass the No. 40 sieve. Therefore, it is recommended that a grinder be employed, as shown in Fig 4.5, to break down all soil

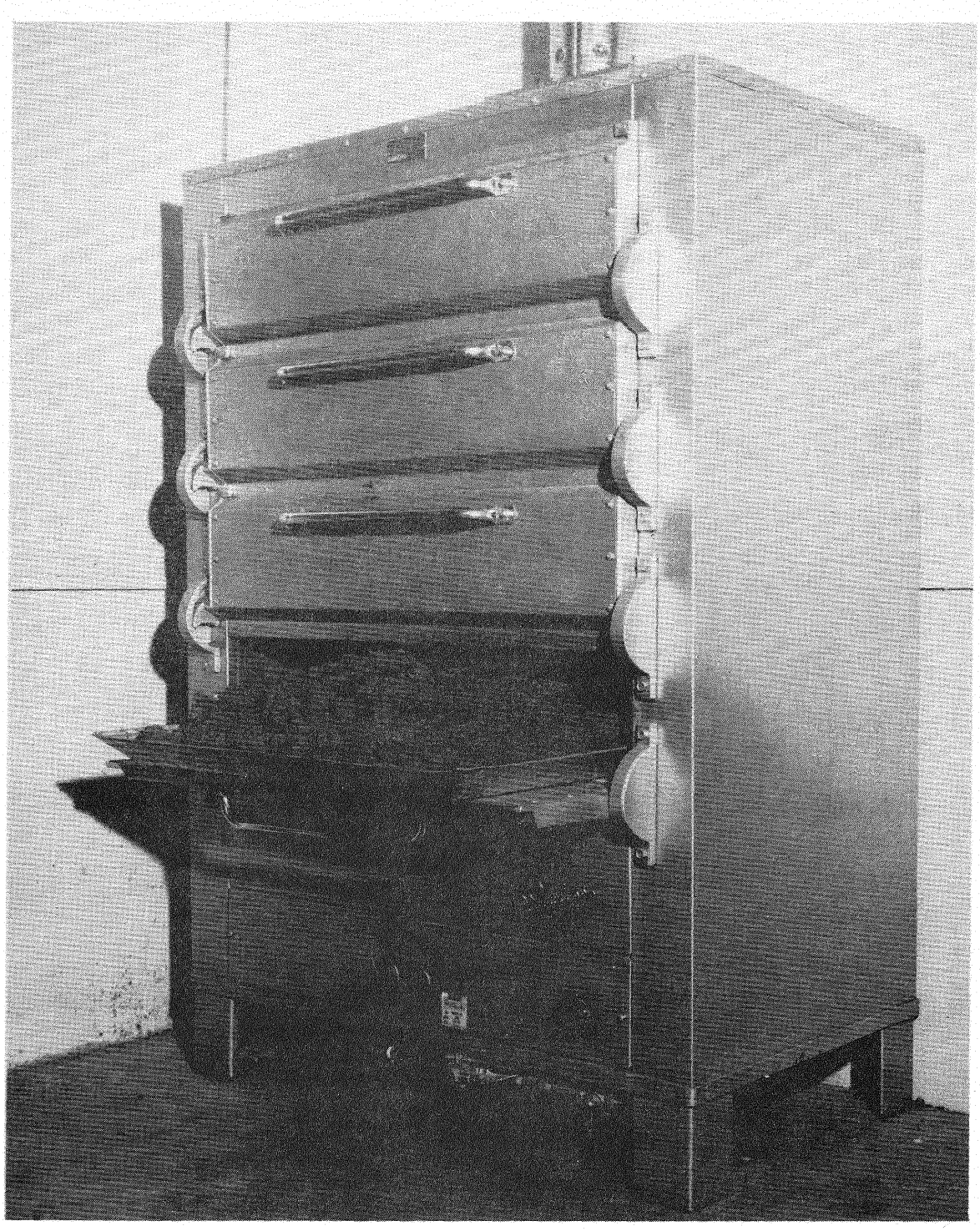


Figure 4.2. Oven and Dry Soil

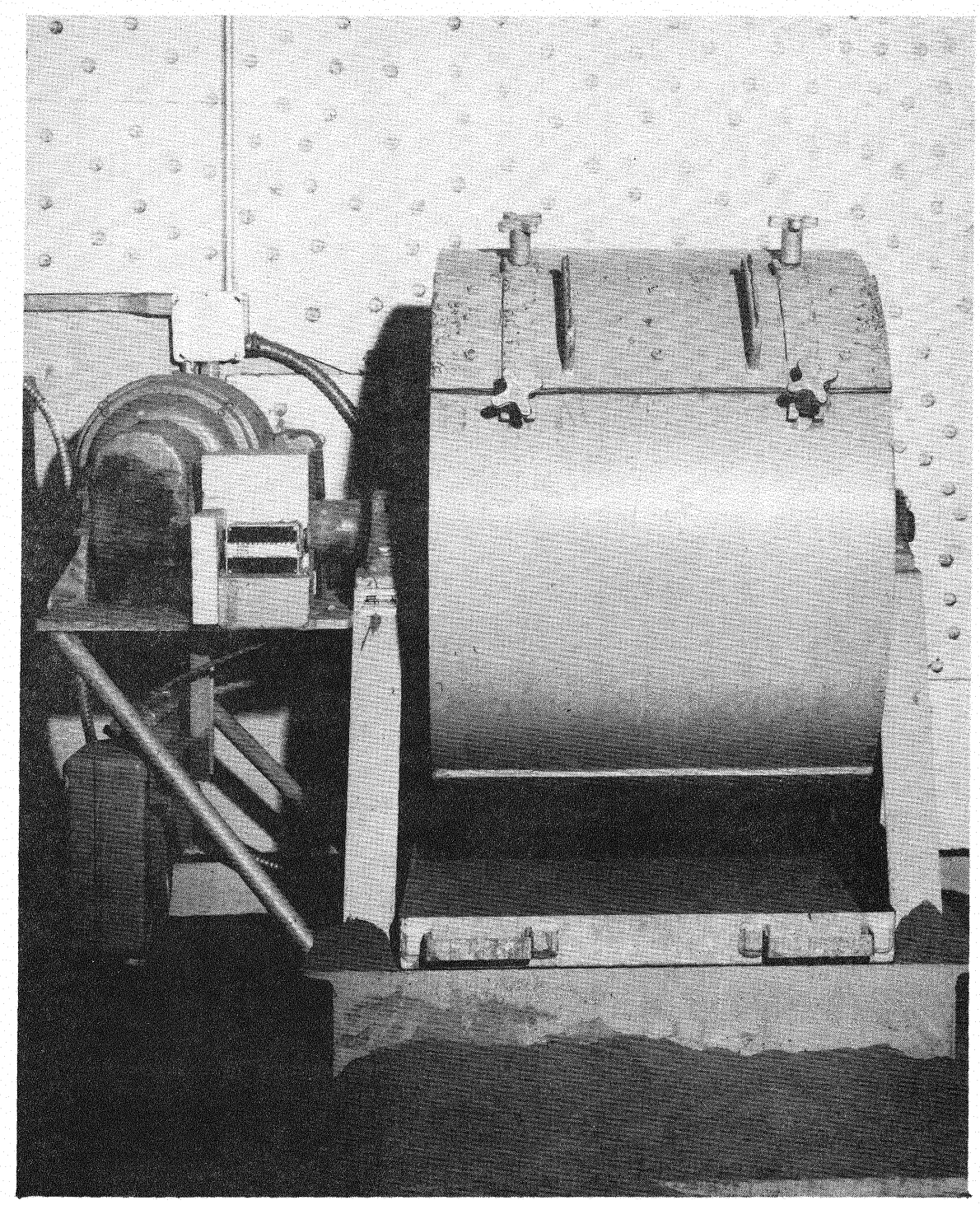


Figure 4.3. Los Angeles Abrasion Test Machine

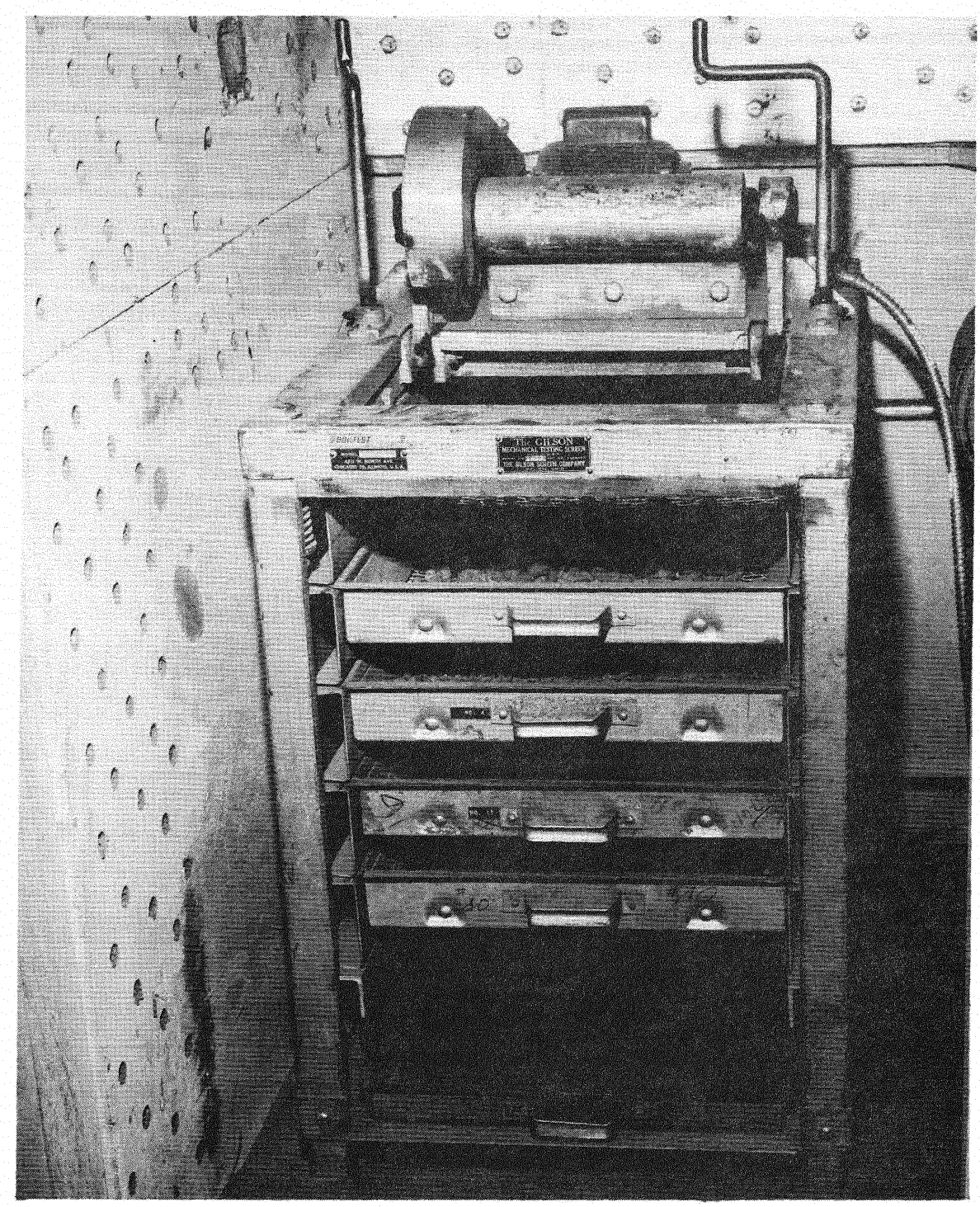


Figure 4.4 Gilson Mechanical Testing Screen

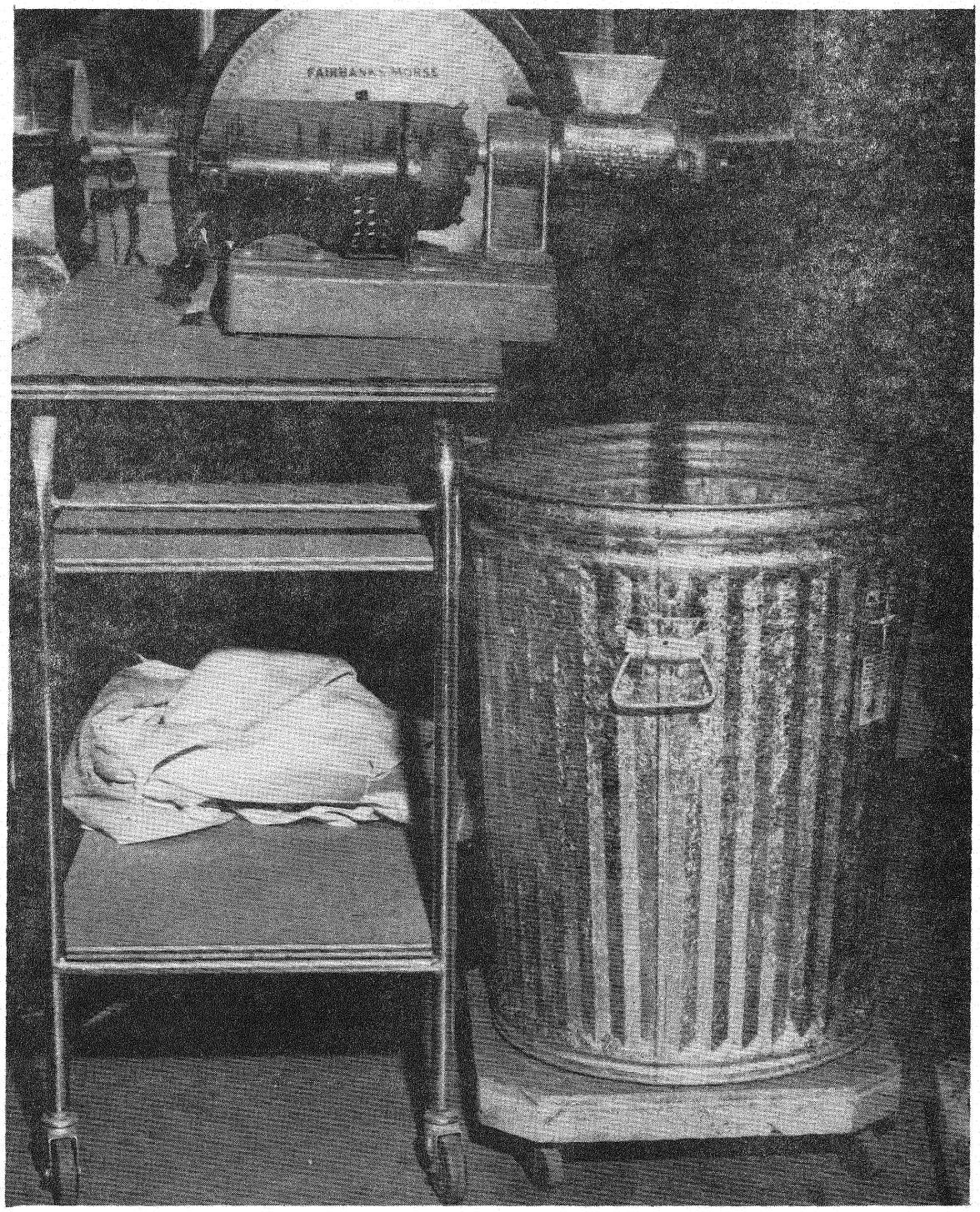


Figure 4.5. Soil Grinder

retained on the No. 40 sieve. Otherwise, the time required for processing highly plastic clays is extremely long. The silty clay broke down quite easily in less than thirty minutes per thirty pound load. Its yield (passing the No. 40 sieve) was above sixty per cent and any material retained was pulverized in the grinder. The soil before and after processing is shown in Fig 4.6 in the G.I. storage cans.

It should be noted that if highly plastic clays are being processed by the above procedure all personnel in the immediate working area should wear face masks to prevent inhaling the dust. The clay size particles remain in suspension indefinitely if proper ventilation of the area is not available. This creates a definite health hazard for personnel involved.

Container Preparation

A fifty-five gallon drum was cut down to a height of approximately twenty-four inches, as seen in Fig 4.7. The inside was painted with red lead and then with a coat of epoxy of prevent corrosion. A drainage outlet of galvanized pipe fittings was placed on each barrel. A plywood template was cut to fit under the barrel to keep deformation of the bottom at a minimum during compaction. Each barrel rested on a channel frame. The drainage outlet, template, and steel frame are shown in Fig 4.8. A steel frame and hoist, shown in Fig 4.9, was used to move the compacted standards, which weighed over six hundred pounds when completed.

After painting, each barrel was filled with water to a predetermined mark (twenty-one inches in this study). This mark represented the proposed top of the soil mass after compaction. The barrel was weighed and the volume of the container to this specified mark was

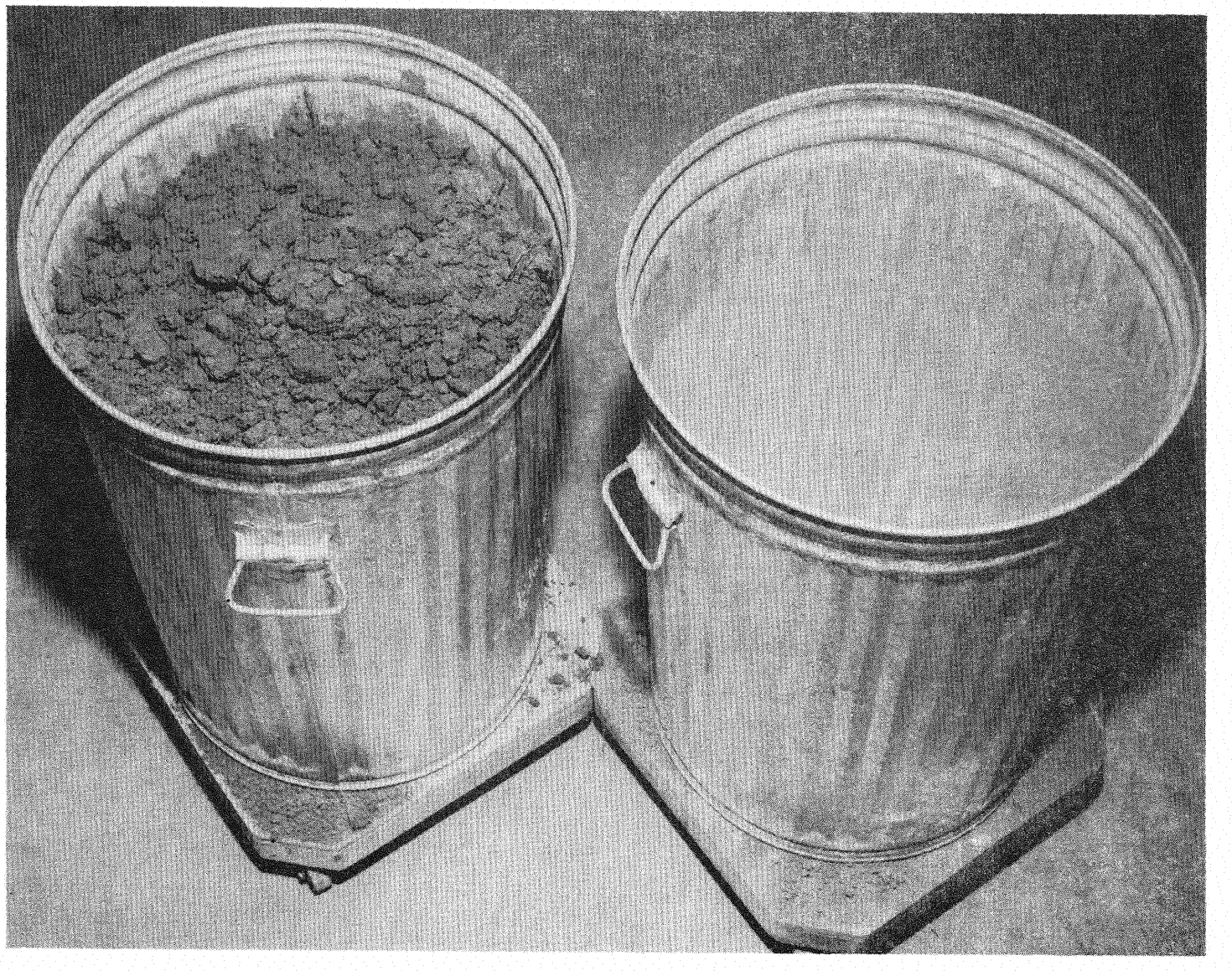


Figure 4.6. Soil Before and After Processing

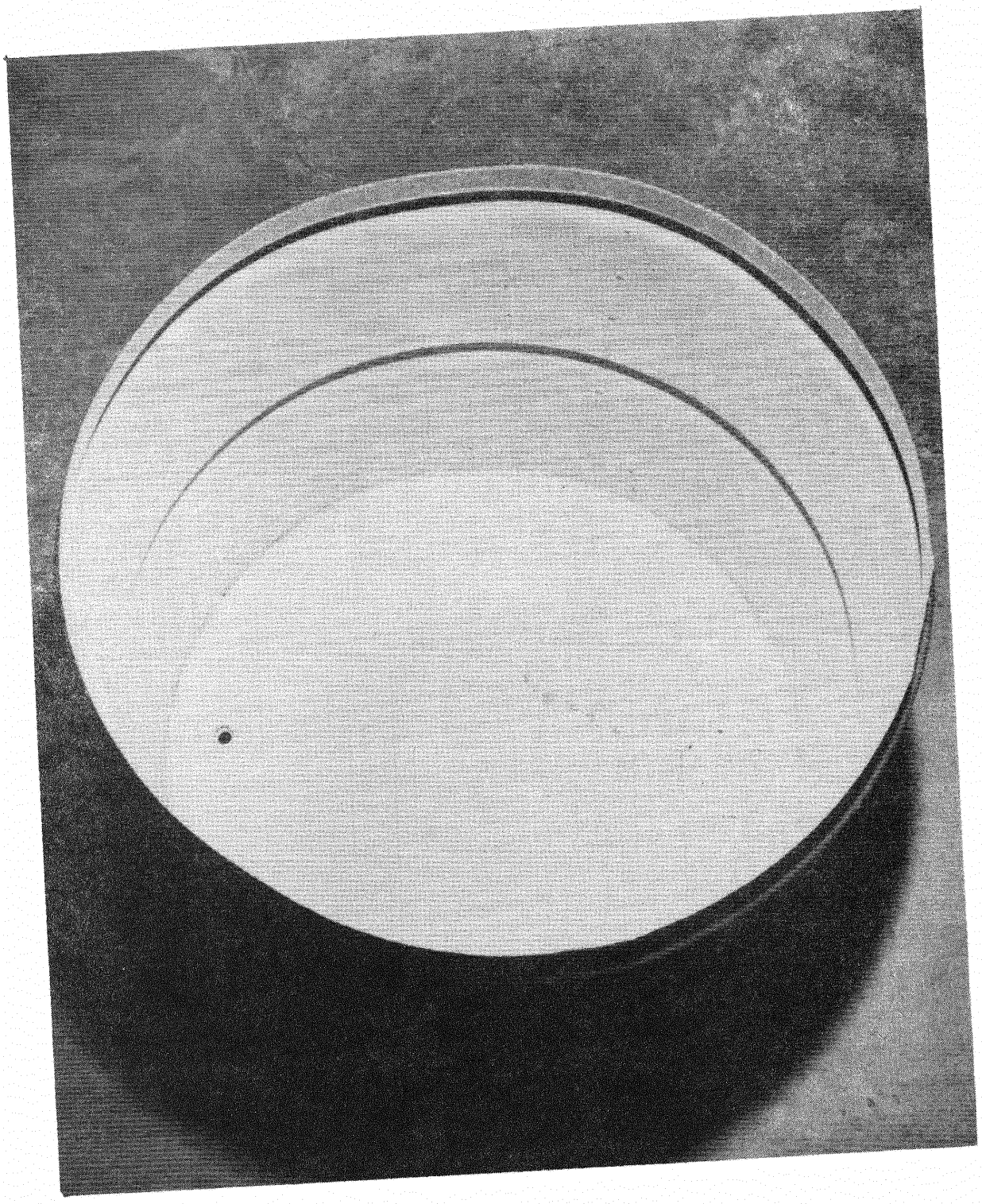


Figure 4.7. Empty Standard Container

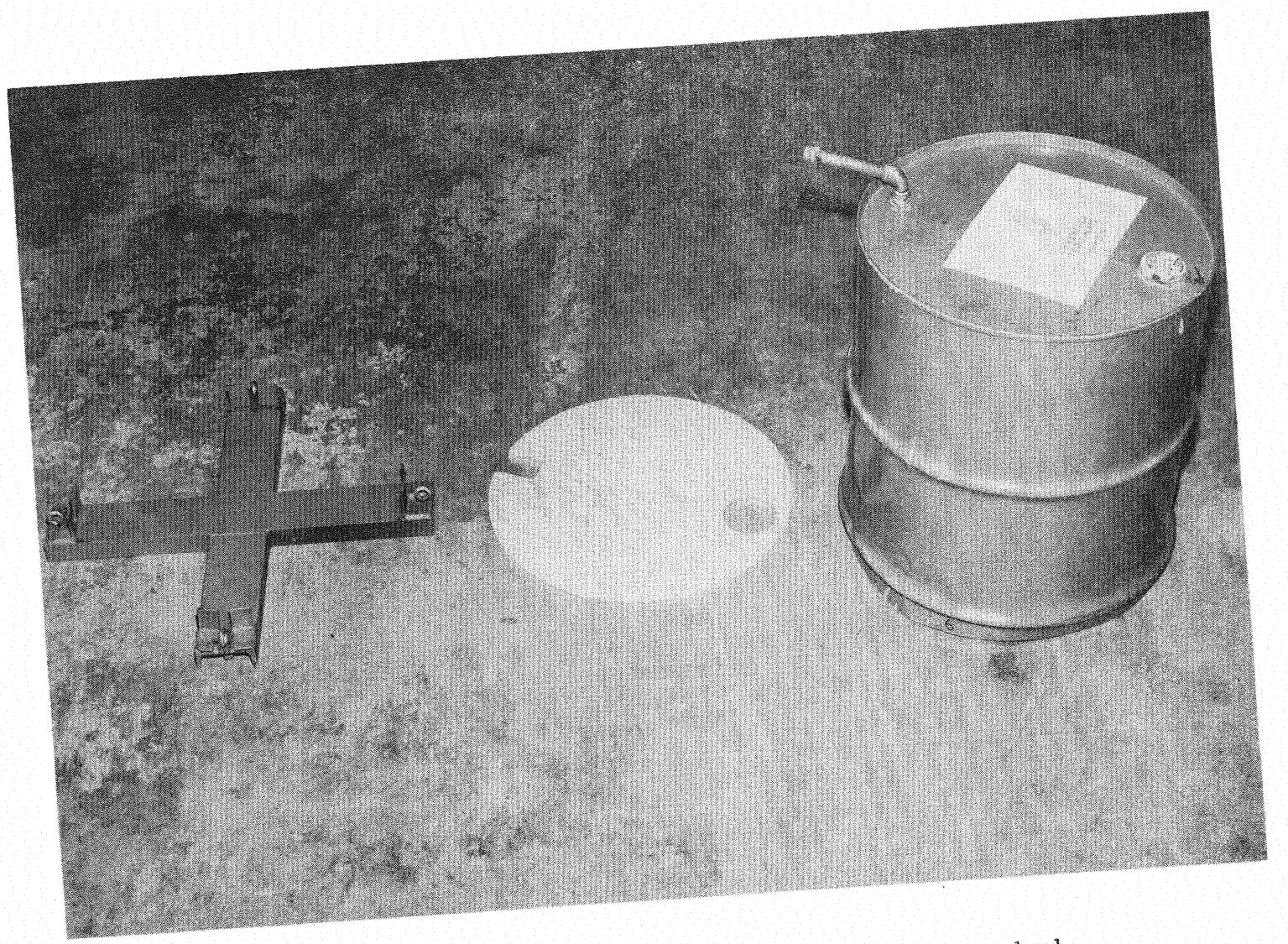


Figure 4.8. Steel Frame, Plywood Template, and Standard Container with Drainage Facility

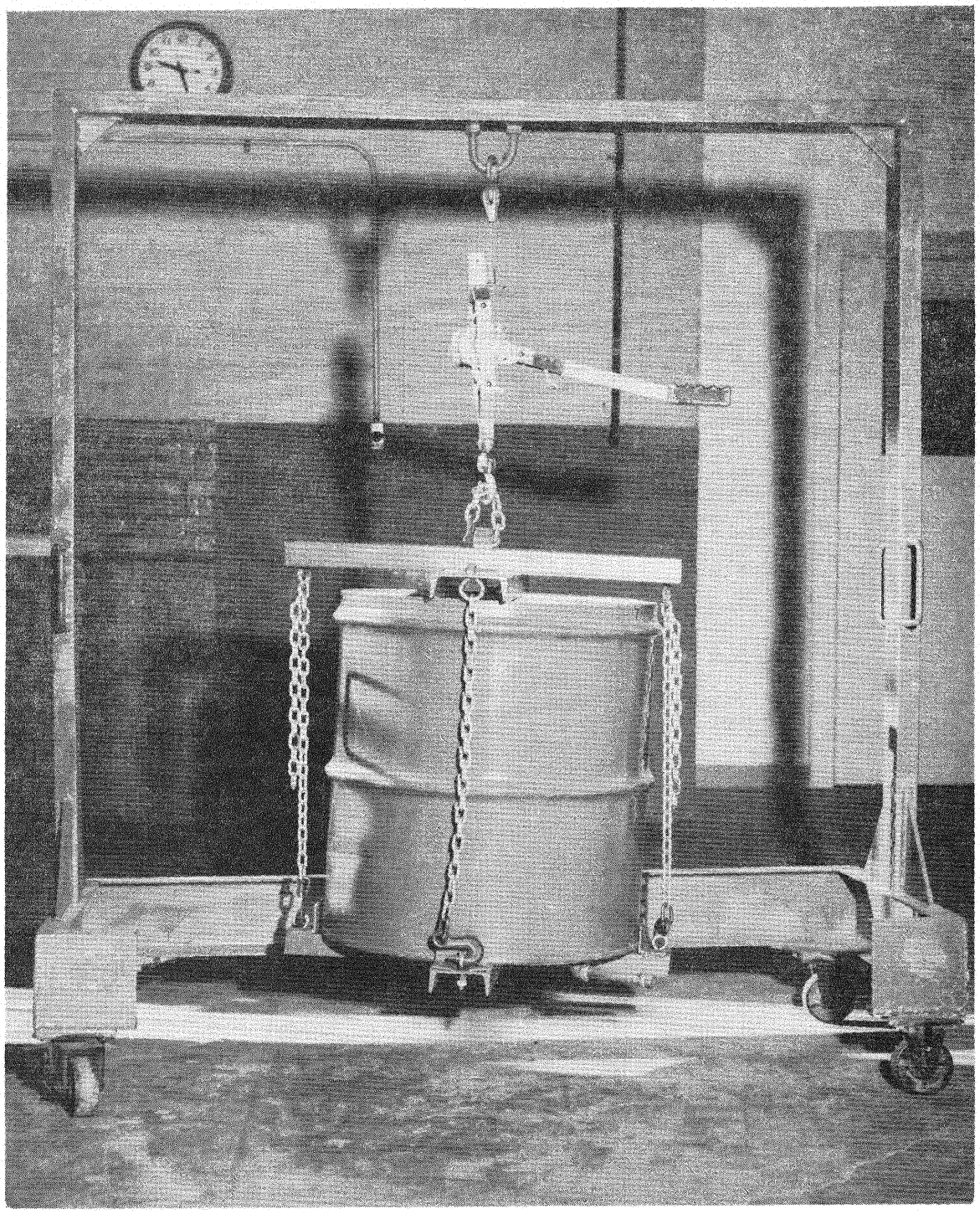


Figure 4.9 Steel Frame and Hoist

determined from weight of water calculations.

Construction of Standards

All materials were mixed and compacted in three inch lifts. The uniform sand had a very narrow range of obtainable void ratios. Therefore, its minimum void ratio (e = 0.67) was selected as the design value. The minimum moisture content for the standard (based on Eq 3.1) was calculated in lb per cu ft and converted to engineering moisture content. Five moisture contents were chosen for the set of standards. Therefore, with void ratio and moisture content selected as control values, the amount of water and sand for a compacted three inch lift was calculated.

The two cohesive soils were prepared in similar manner. Using Harvard Miniature apparatus, Standard and Modified AASHO compaction curves were developed and the minimum allowable moisture content for an eleven inch sphere of influence was calculated from Eq 3.1. These data are shown in Fig 4.10 and Fig 4.11 for the PRC and silty clay. Moisture contents for the PRC standards were selected between 16% and 25%. Note that standards No. 8 and No. 9 are at or above the plastic limit. The silty clay standards were chosen between 9% and 18%. Standard No. 10 was mixed to obtain a moisture content which theoretically would allow the sphere of influence outside the container. Standard No. 13 was at the plastic limit of the soil.

Also, it was desired to obtain a large range of wet density values since the standards would be used for density probe calibration research. The design void ratios of the cohesive materials were selected based on the compaction curves obtained. Points above the Modified AASHO curve and below the Standard AASHO curve were included

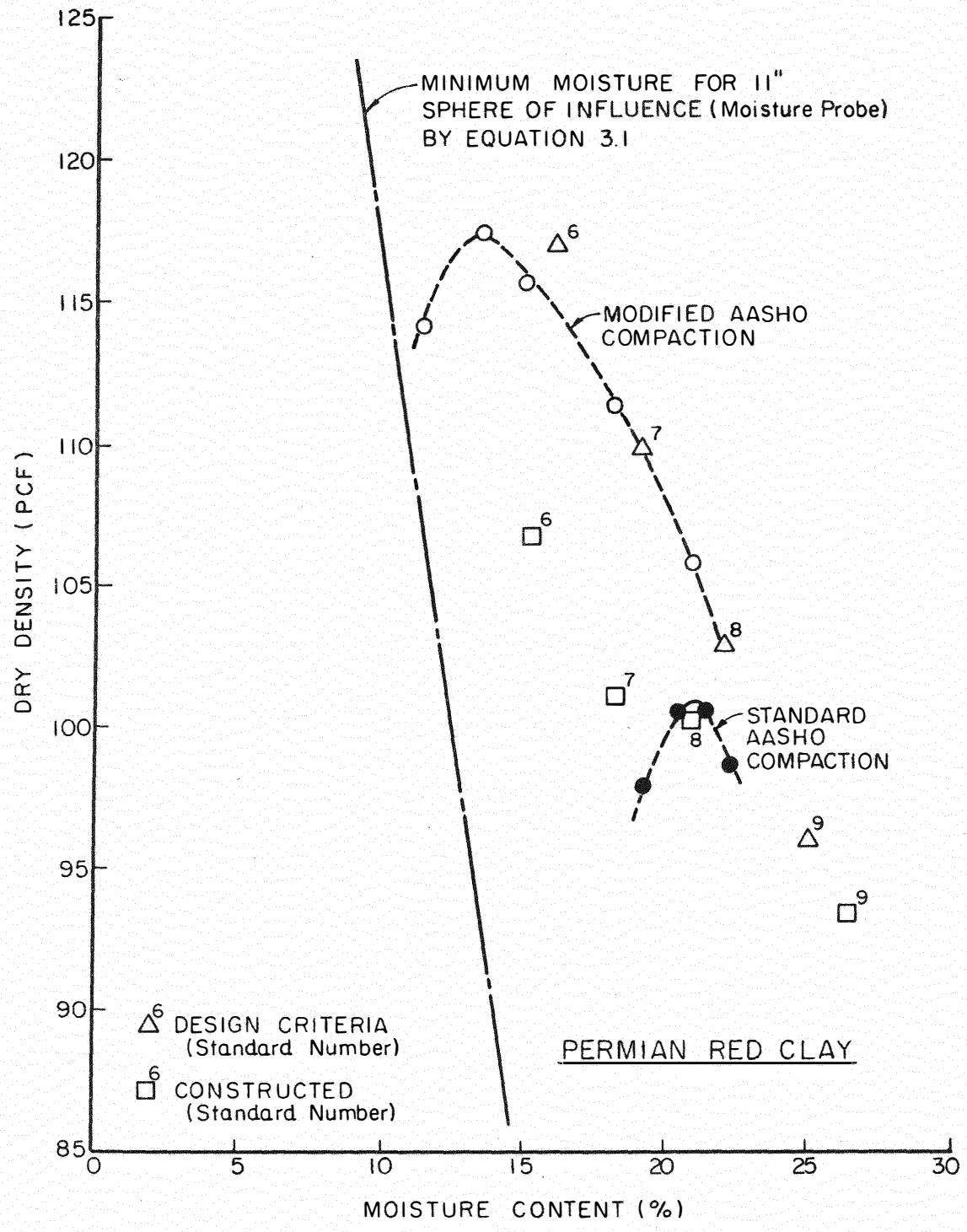


Figure 4.10. Compaction Curves, Permian Red Clay

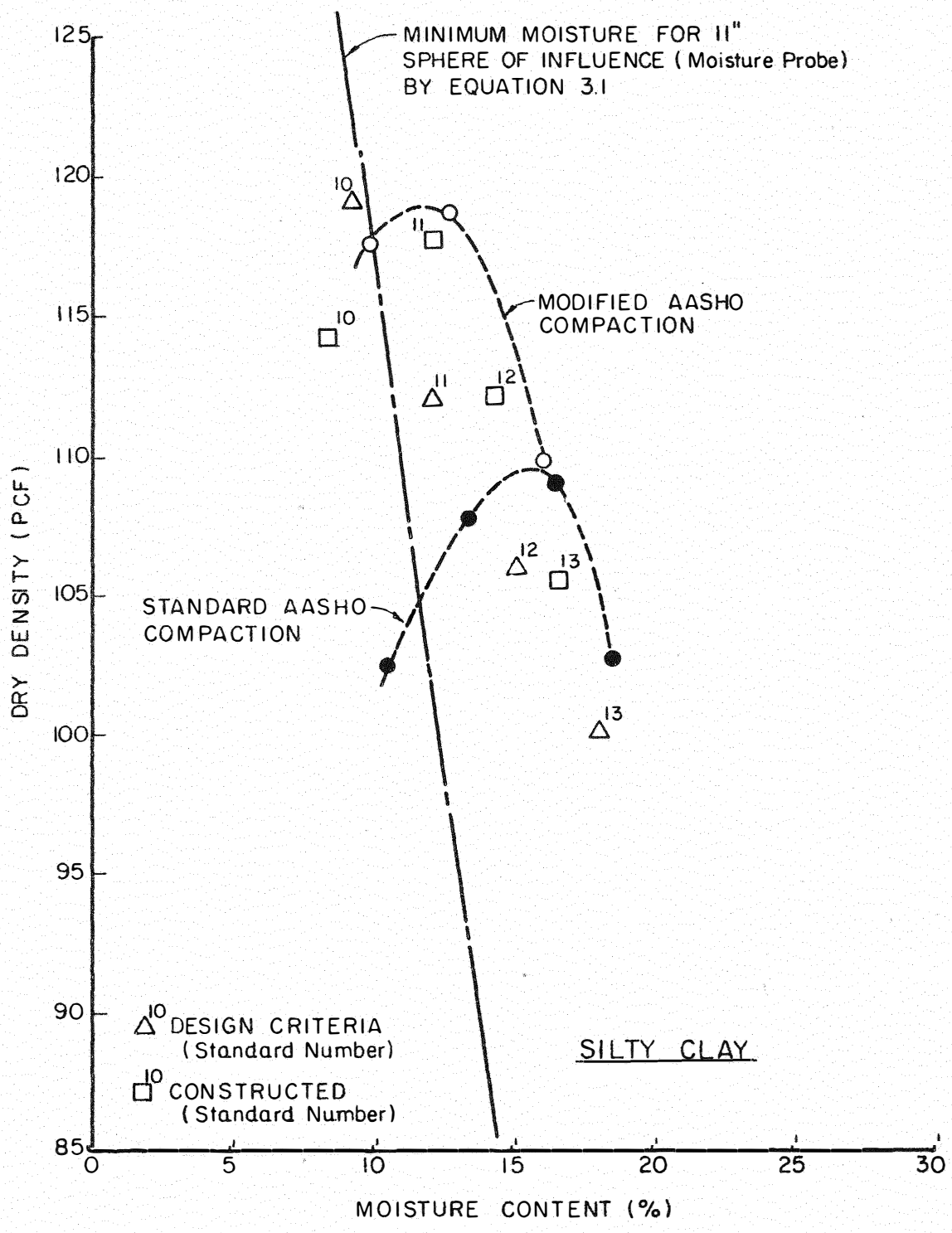


Figure 4.11. Compaction Curves, Silty Clay

to determine the most efficient region of compaction with the equipment available.

The correct amounts of soil and water were weighed and mixed until well blended. Hand mixing was employed in all cases as shown in Fig 4.12. The processed cohesive soils were assumed to have an initial moisture content of two per cent. Hand mixing was selected because it is the only quick method of working with clays in dry powder form. Water was added and the mixture troweled thoroughly. No spraying was used because of evaporation problems.

Once the soil and water were mixed, the "mud" was shoveled into the standard, as is shown in Fig 4.13, and compacted immediately with a power tamp as shown in Fig 4.14. Three inch gradation marks were placed on the inside wall of the drum prior to compacting, and the soil was compacted until each mix of soil and water filled the three-inch lift. Seven lifts were placed in each standard. The barrel was covered with polyethylene sheeting to prevent evaporation. A compacted standard and evaporation cover are shown in Fig 4.15.

It should be noted that this approach to the compaction phase eliminated any problems with timing or otherwise controlling the compactive effort applied to each lift. The lift was compacted until it fit the design requirements and the three inch lift thickness was achieved.

Later, the standard was weighed to determine the weight of the soil mass. Using the volumes previously determined, the average mass density of the soil was determined.

The sand standards were allowed to cure for ninety days, the PRC, forty-five days, and the silty clay, fifteen days. The standard construc-

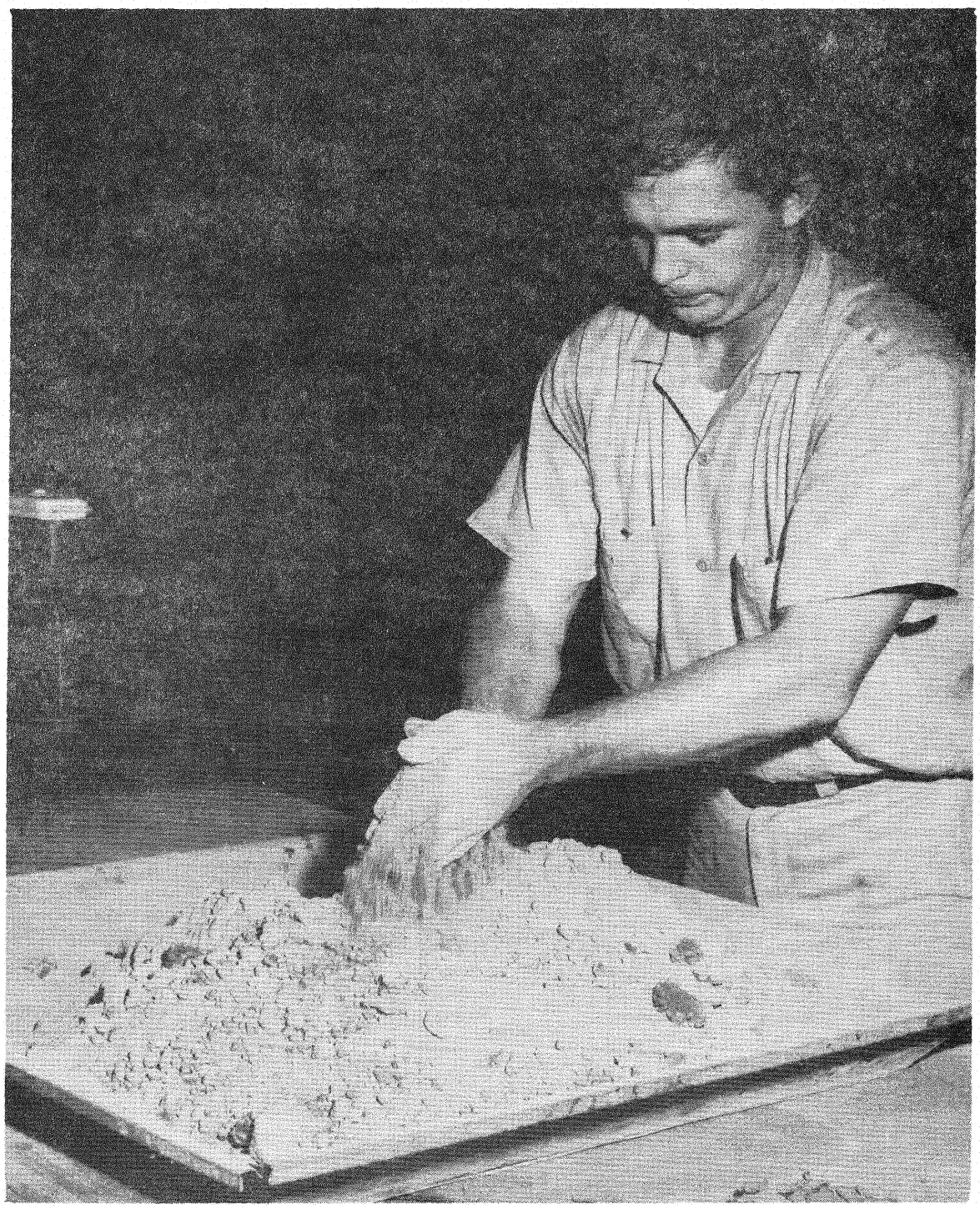


Figure 4.12. Hand Mixing Procedure

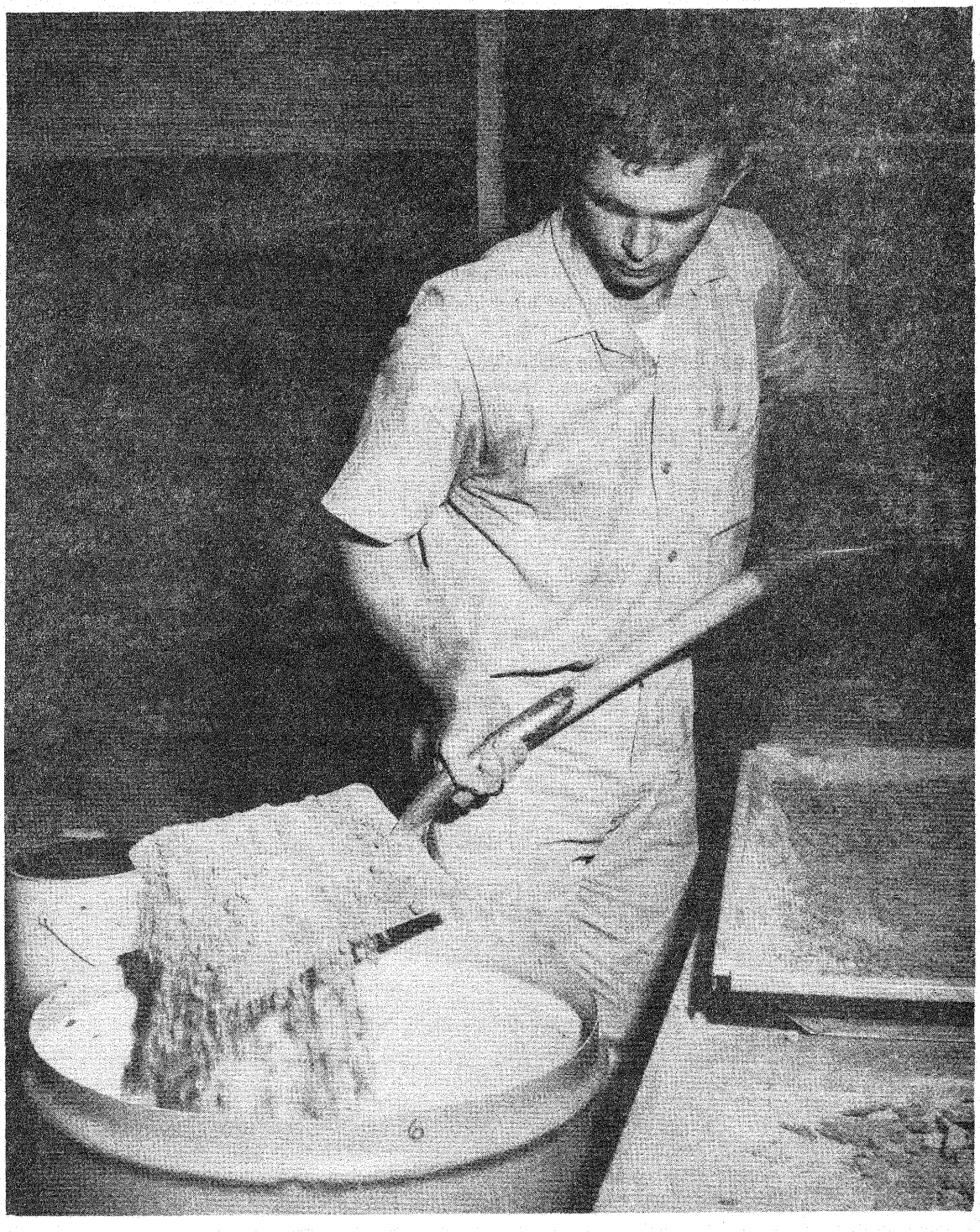


Figure 4.13. Lift Placement

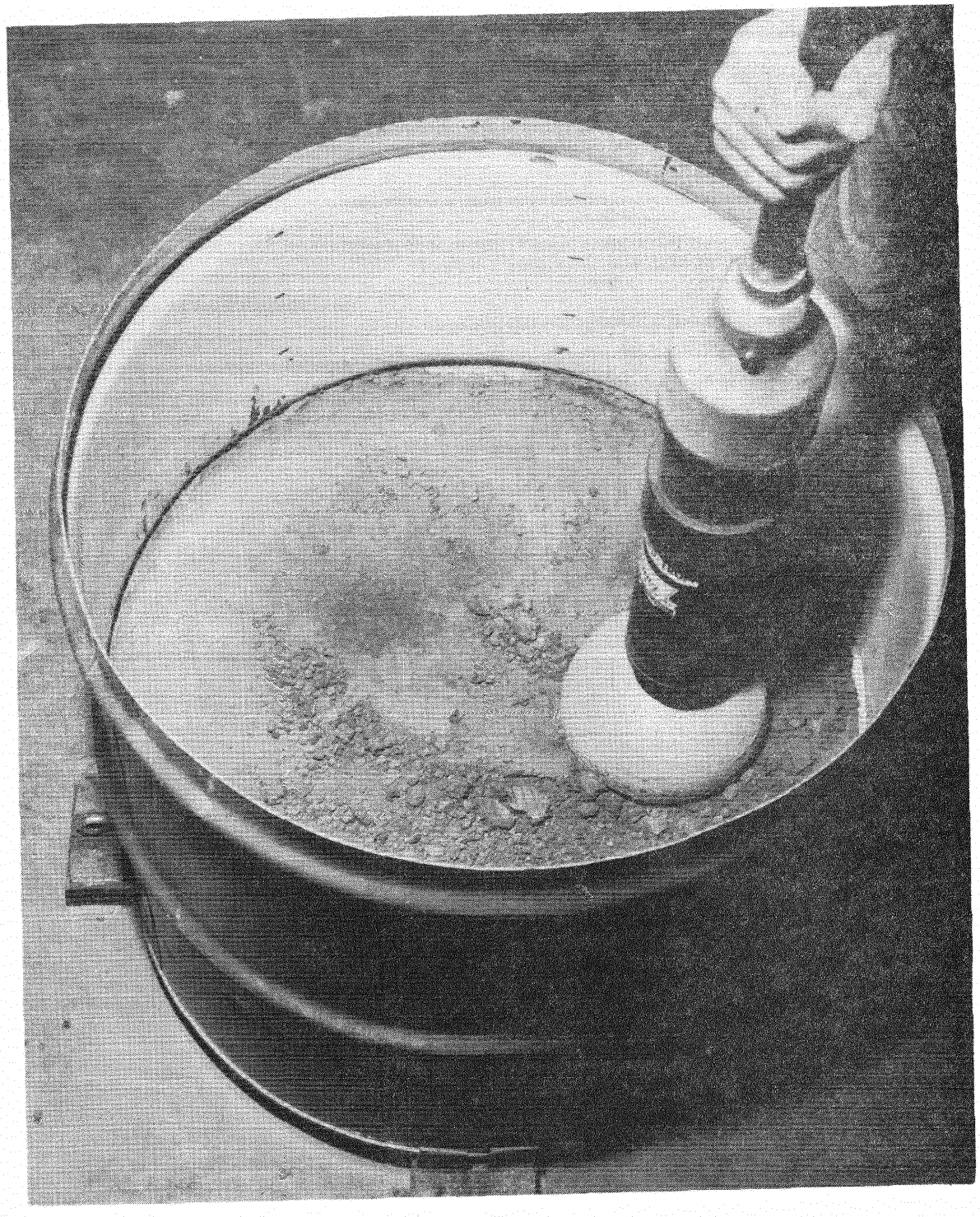


Figure 4.14. Compaction Procedure

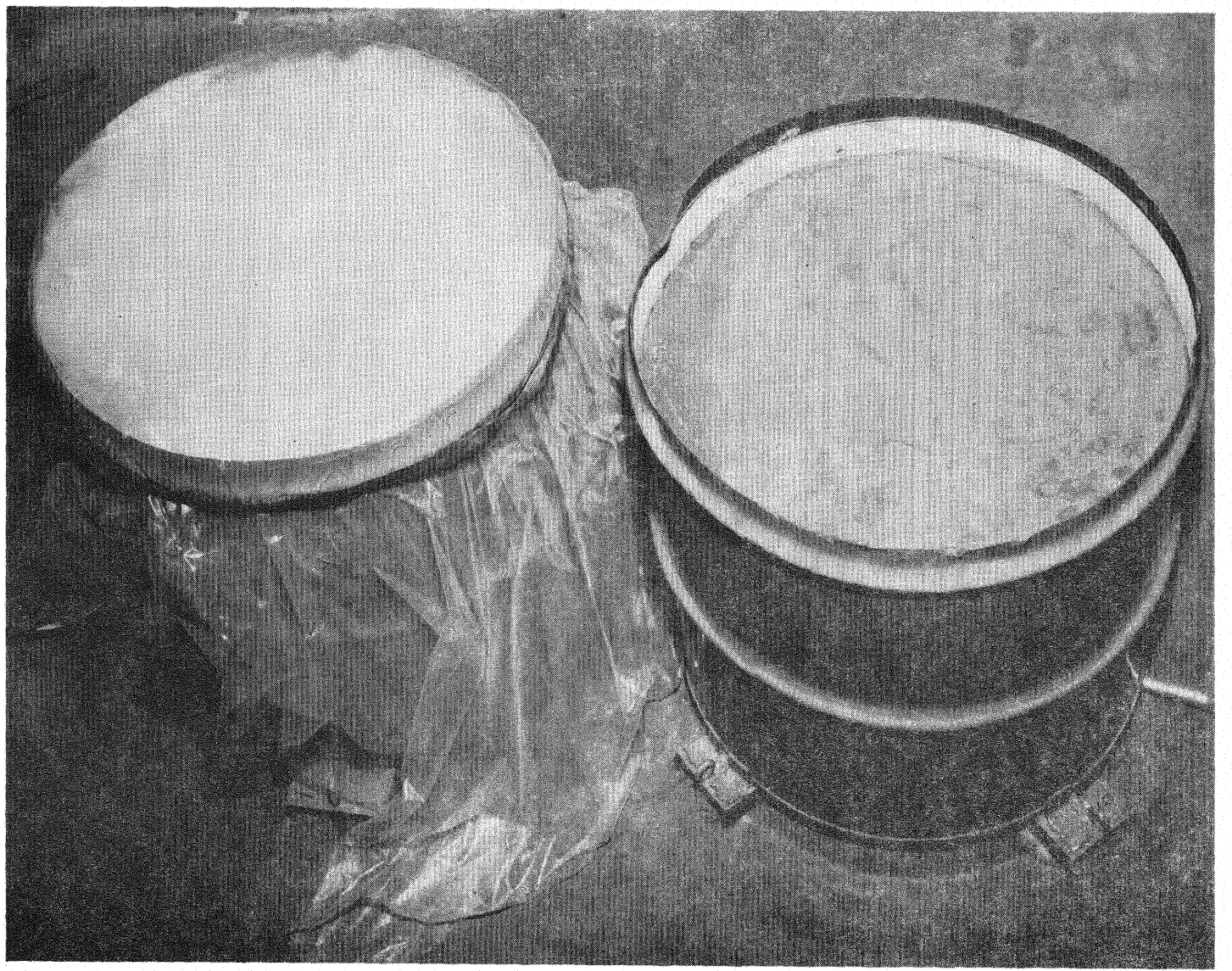


Figure 4.15. Standards without Access Tubing

tion schedule created the variation in curing times as access tubing for the entire group of standards was placed during one continuous operation. Furthermore, the volume of soil required for four or five standards made it impractical to store all soils and compact the standards at one time. Therefore, the three types were compacted at intervals, requiring the storage of only one soil at a time.

To install the aluminum access tubing, a two inch OD thin wall stainless steel tube was pushed slowly into the center of the compacted soil. This tube had a 1/16 inch wall thickness and was honed at one end to minimize soil disturbance as it was forced into the clay. The equipment and procedure are illustrated in Figs 4.16 and 4.17. A wooden guide template was placed on the soil surface to guide the tube into the standard. The cutting tube was pushed by a Tinius Olsen 200,000 pound universal testing machine. The steel tube was removed with an overhead crane and moisture samples were taken from the cored soil. An aluminum access tube (2.000 inch OD, 1.900 inch ID, 24 inch length) sealed at the bottom was inserted into the cored hole. The standard was recovered with polyethelene sheeting to prevent evaporation. A completed standard with access tubing installed is shown in Fig 4.18 and a typical standard cross-section is illustrated in Fig. 4.19.

Discussion of Construction Procedure

The mixing and placement procedures as previously described worked well. Hand mixing of the clay was tedious but it is the best method. The clay near or above the plastic limit is almost impossible to mix with a mechanical mixer as the powdered clay "balls up" in small spheres which are saturated in the center and dry on the surface. The

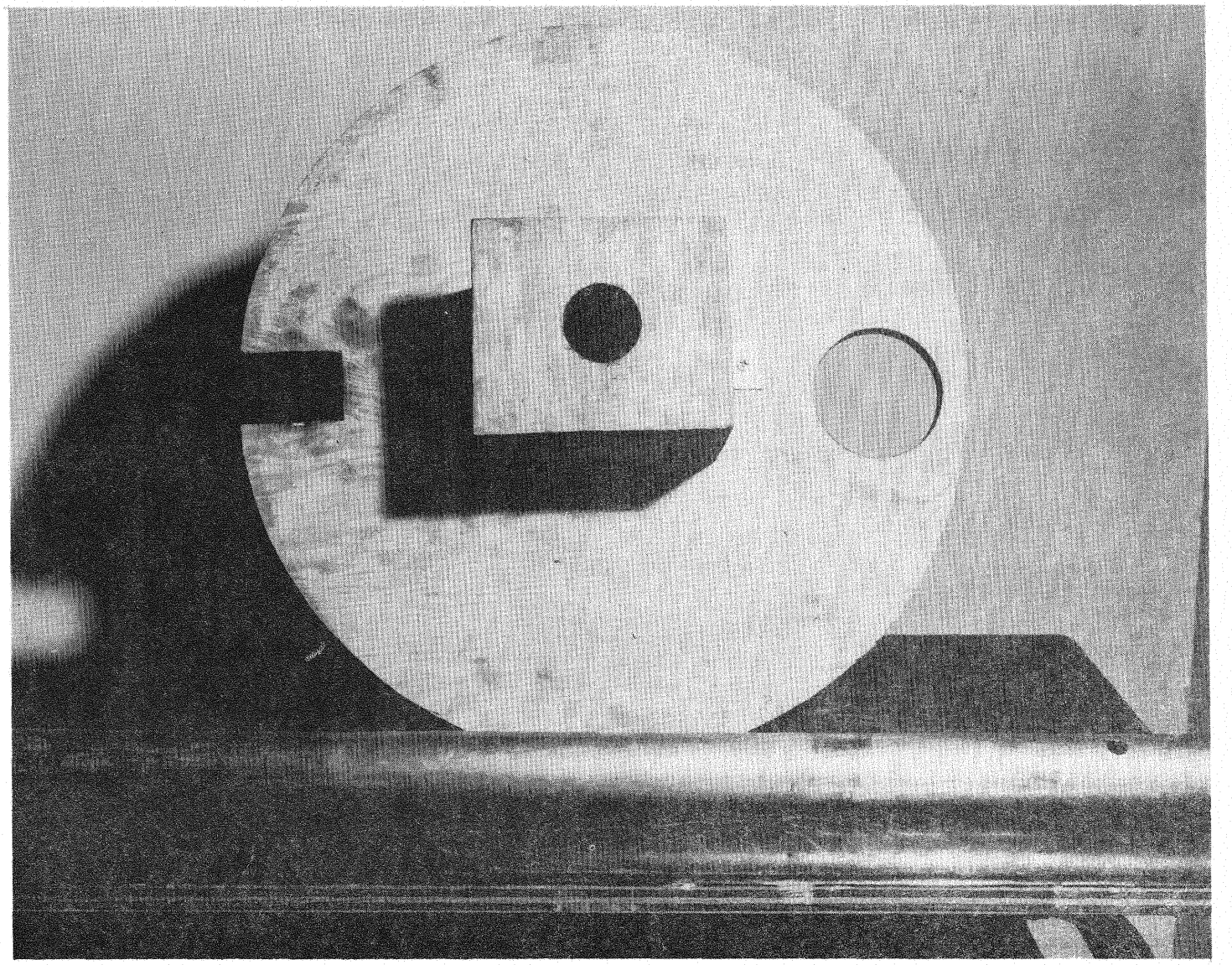


Figure 4.16. Template Guide and Steel Cutting Tube

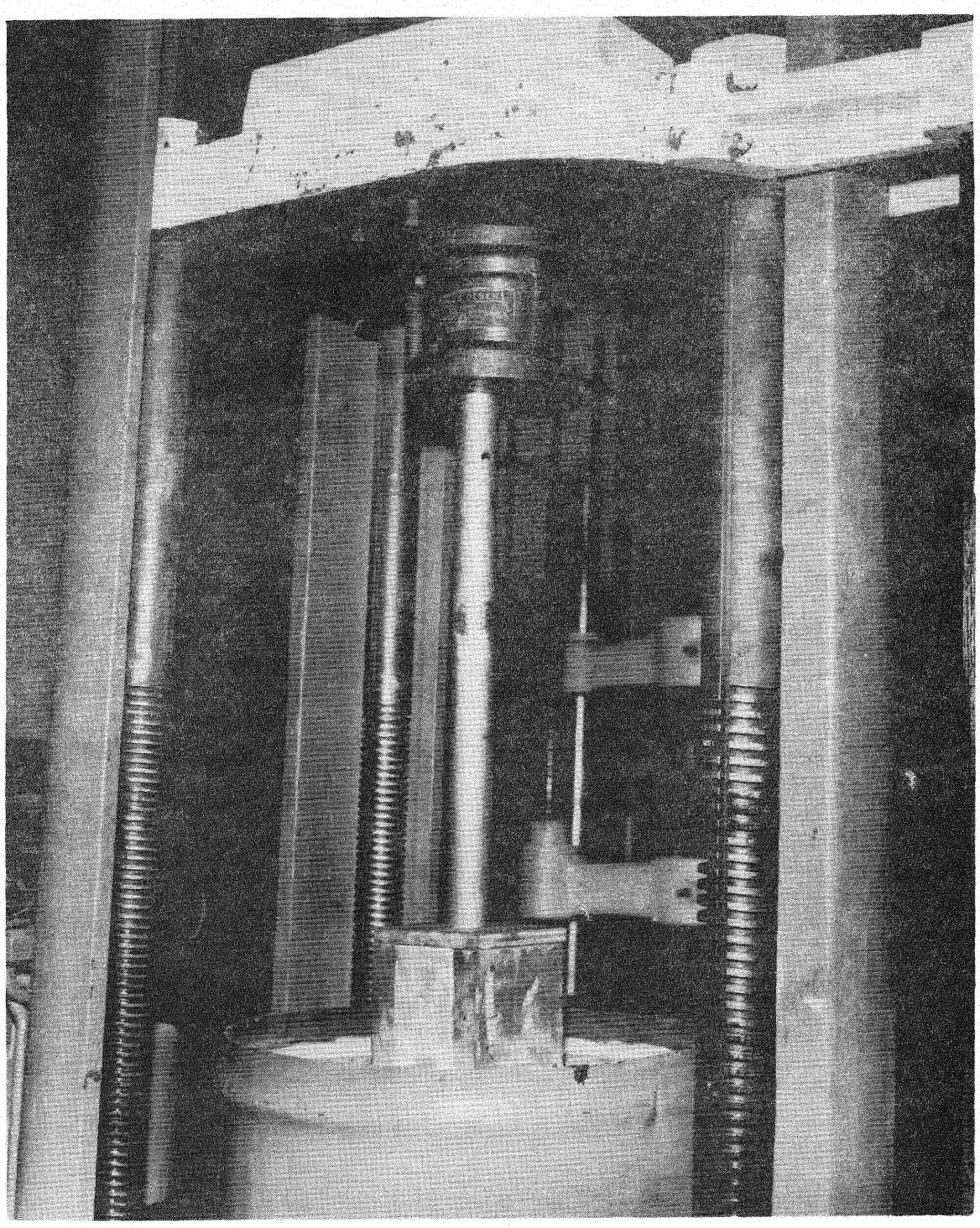


Figure 4.17. Coring Procedure

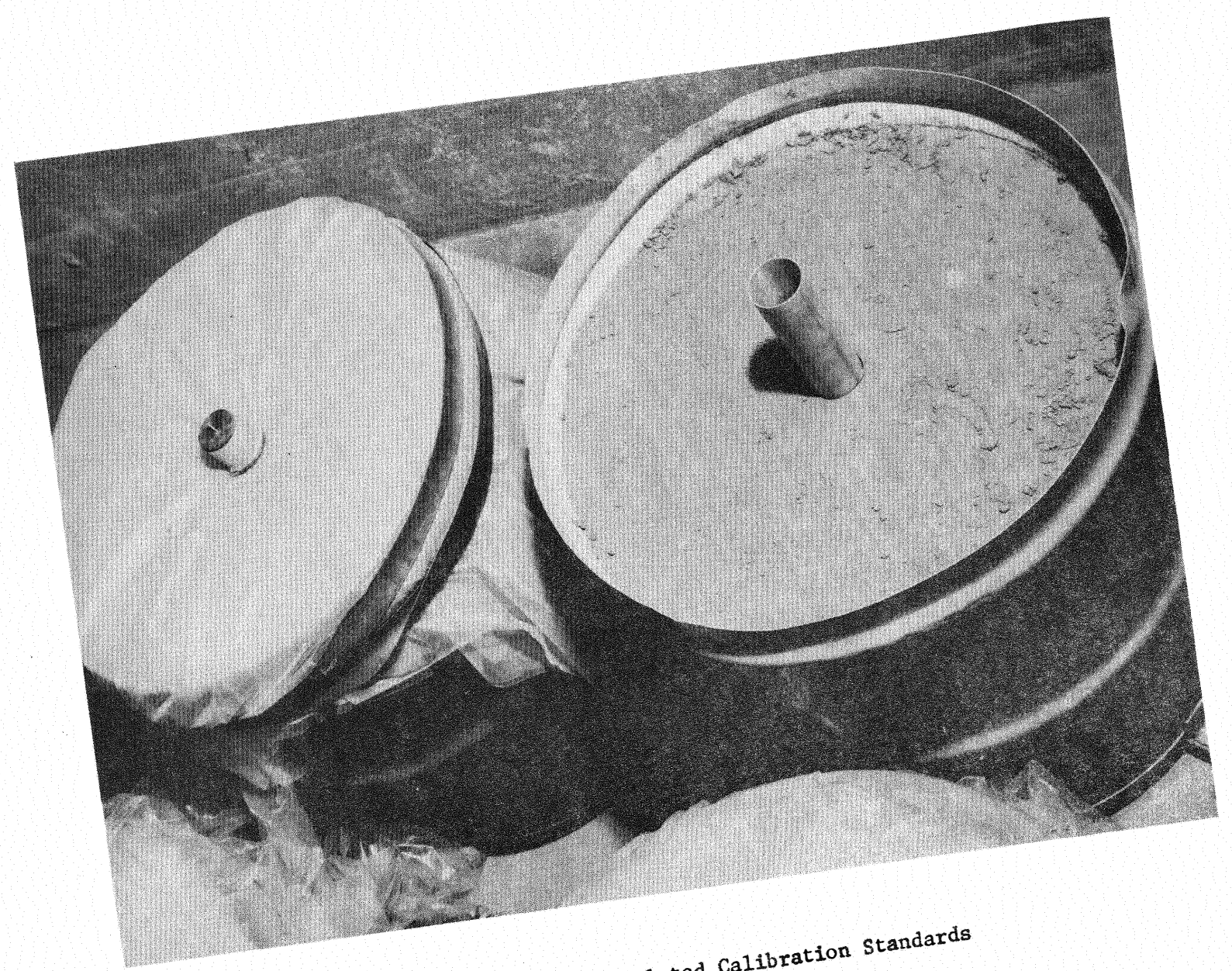


Figure 4.18. Completed Calibration Standards

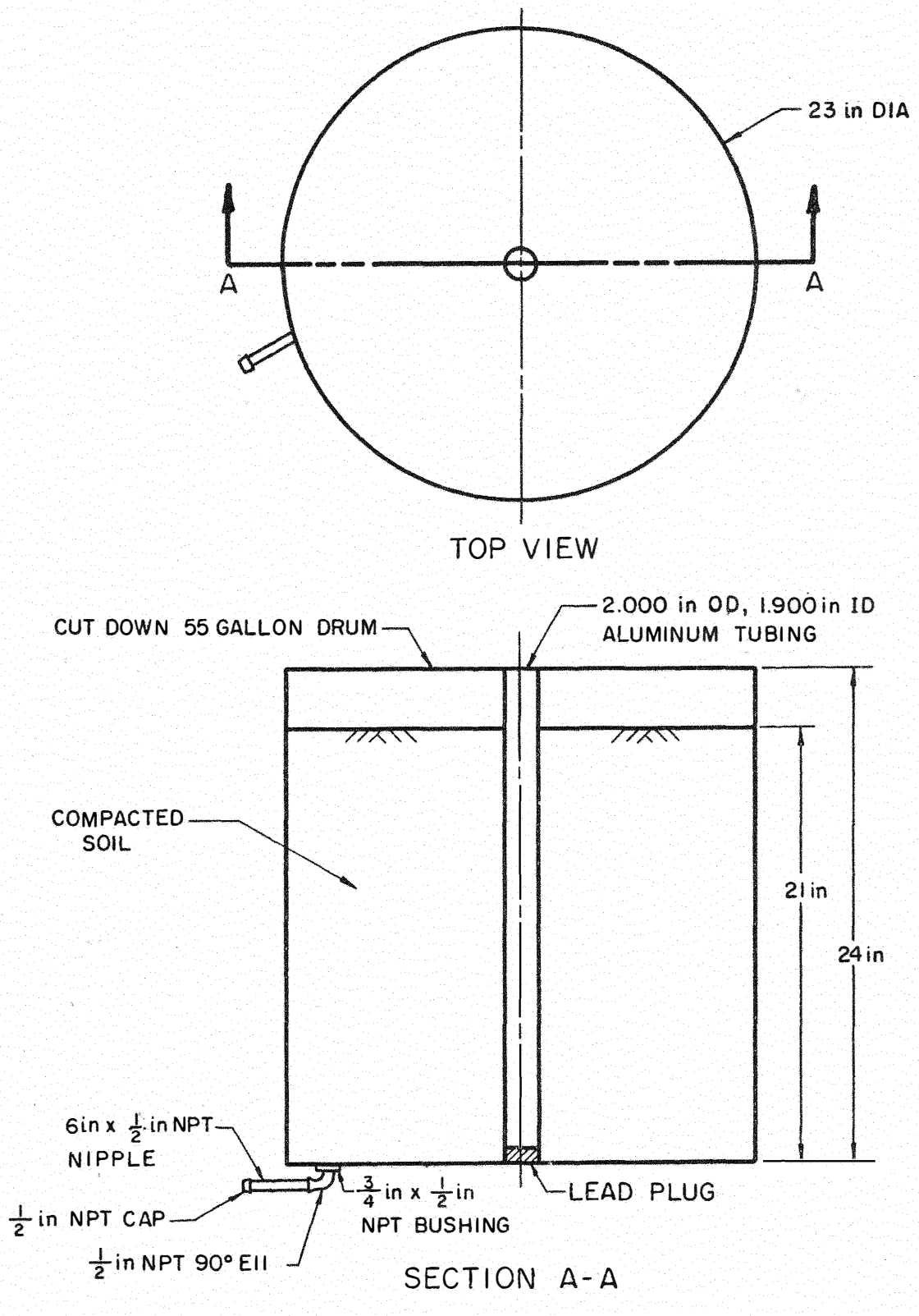


Figure 4.19. Typical Calibration Standard Section

sand mixed well with very little difficulty. Mechanical mixing is a possibility with fine granular soils, especially if thicker lifts are required. The length of mixing time varied with the soil and the moisture content required. However, an average mixing time of fifteen minutes per lift for the silty clay and clay, and ten minutes for the sand is reasonable.

Evaluation of the sand standards was not idealistically simple. The moisture contents were all very near the total saturation value for a void ratio of 0.67. Despite the use of a fine sand to retain moisture by capillary action, the near-saturation states allowed migration of water to the standard bottoms, creating a moisture profile of two to four per cent in the standards. This profile affected both moisture and density probe response in each standard but should not affect bulk density or average moisture content values when correlated with the average probe response for the standard. The maximum and minimum void ratios for the sand were approximately the same, thus future work with sand should incorporate a material with a higher maximum void ratio to allow reasonable moisture contents at lower degrees of saturation. In such case capillary retention of moisture at the desired levels should occur.

Access tube installation was also more difficult in the sand standards. The last two to four inches of saturated sand core did not always remain in the core tube and were difficult to remove from the standard. An attempt to remove one core with a 1 7/8 in. OD auger disturbed the sand around the sides of the cored hole. In most of the sand standards the access tube bottom was thus about two inches above the bottom of the standard. This problem could be eliminated in future work if a 1.5 in. OD auger was used to auger the material from inside.

the 1.875 in. ID coring tube with the coring tube inserted in the standard. The coring tube could then be removed. Slight disturbance of the sand around the coring tube occurred when the tube was pulled. This could be minimized in future work by paying more attention to exact vertical alignment of the tube-pulling apparatus.

Sand Standard No. 2 had a design moisture content at the calculated total saturation for the minimum void ratio. The lifts in this standard did not compact well and the sand began to bulk which indicated total saturation. This behavior verified the void ratio calculations for the sand. Attempts to vary the sand void ratio failed because of uniformity of the material.

The main problem encountered with the cohesive soil was in mixing. Placement was done efficiently with the power tamp in most cases. However, standards No. 6 and No. 10 were designed above the Modified AASHO curves for the respective materials. As can be seen in Figs 4.9 and 4.10, the constructed standards had good moisture contents when compared to the design criteria, but the average bulk densities were not fulfilled. It is believed that the Modified AASHO curve represents the limit of compaction capabilities for this procedure and equipment. Standard No. 10 is designed to have a moisture content less than that required by Eq 3.1 for the standard container. The significance of this point will be discussed in Chapter 5.

Generally, the moisture contents of the cohesive standards were close to design specifications, but the density values were somewhat less. The dry density figures were computed on the basis of average wet density data.

A possible source of human error in this procedure could be in

weighing. Volumes for the standard containers varied between 4.66 cubic feet and 4.92 cubic feet. An average value was 4.8 cubic feet for the volume of a compacted soil mass. The platform balance used was accurate to one-half pound. It should be noted that a large error of five pounds made in weighing the water filled barrel would alter the average bulk density by three lb per cu ft. The same error when determining the soil weight would alter the average bulk density about two lb per cu ft.

Another possible source of error was the estimate of initial water content of the soil. However, as stated previously, the constructed standards had moisture contents quite close to the design criteria. It is believed that this factor was not in error. It should be standard procedure to store clay soils in sealed containers to keep the soil from absorbing large amounts of water from the atmosphere.

The core moisture samples from the cohesive soil standards were quite uniform with a variance of less than one per cent moisture content. This is considerably less than one lb per cu ft in any of these standards.

The access tubing fit tightly in the cohesive soils with an absolute minimum of air gap between soil and tube wall. The outside of the steel cutting tube was lubricated with silicon grease to prevent soil disturbance. It worked well for the clay soils. In contrast, the access tubing in the sand standards did not fit quite as tightly.

Data Collection Procedure

Probe readings were taken at one inch intervals starting at the bottom of the access tube and progressing upward. The data taken at each level consisted of 10 one-minute counts which placed the pulse response at the ninety-nine per cent confidence level with a statistical

deviation of less than one per cent (Ref 18). The probe was moved toward the top of the standard until a large deviation in equipment response was noted.

Ten standard counts, each of one minute duration, were taken before and after each series of data readings. The standard count is the probe response in its protective shield, which acts as a secondary reference standard.

Typical probe responses are shown in Fig 4.20 for the density probe and Fig 4.21 for the moisture probe. The term C_r is the count ratio, or the ratio between probe response in the calibration standard and the average count in the reference standard.

The density response is of particular interest. The small decrease in probe response is understandable as the probe is raised from the bottom of the access tubing. The probe is no longer influenced by the bottom of the barrel or the lead plug in the access tubing. However, as the probe reached about the four inch level (from bottom of tube to bottom of probe) a decrease in C_r was noted. This was characteristic of all the cohesive soil standards. It is thought that the compaction procedure employed produced this effect. The standard barrel was most stable in the steel frame during compaction of the third, fourth, and fifth lifts. The most efficient compaction was developed in this region and in the soil immediately below it. Part of the compactive effort in the upper lifts was transmitted to the lower levels, causing an area of higher densification. As the probe approached the surface of the standard, the C_r was influenced greatly as is illustrated by the sharp increase in pulse count. Such response does not give valid indication of density at

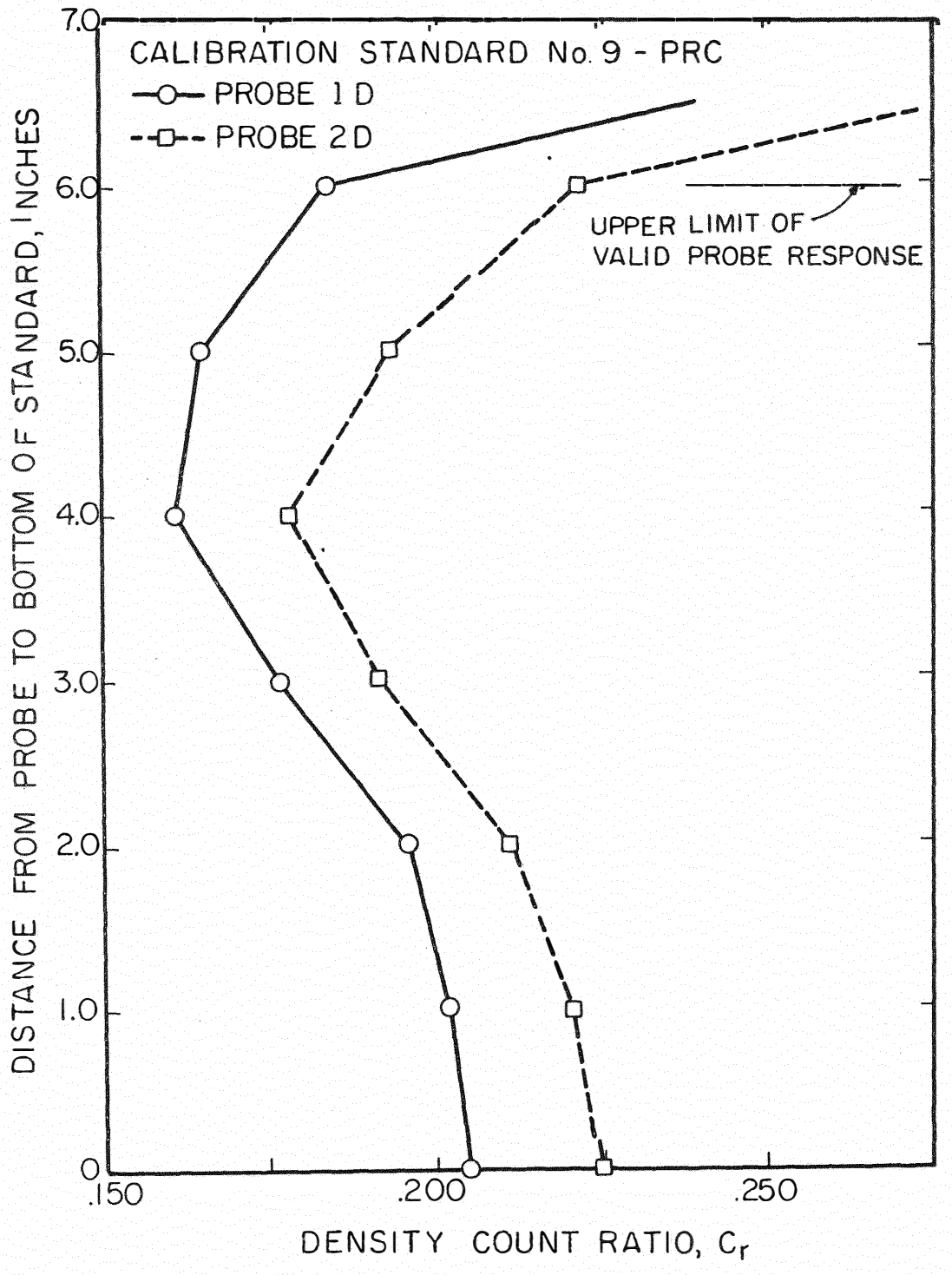


Figure 4.20. Typical Density Probe Response

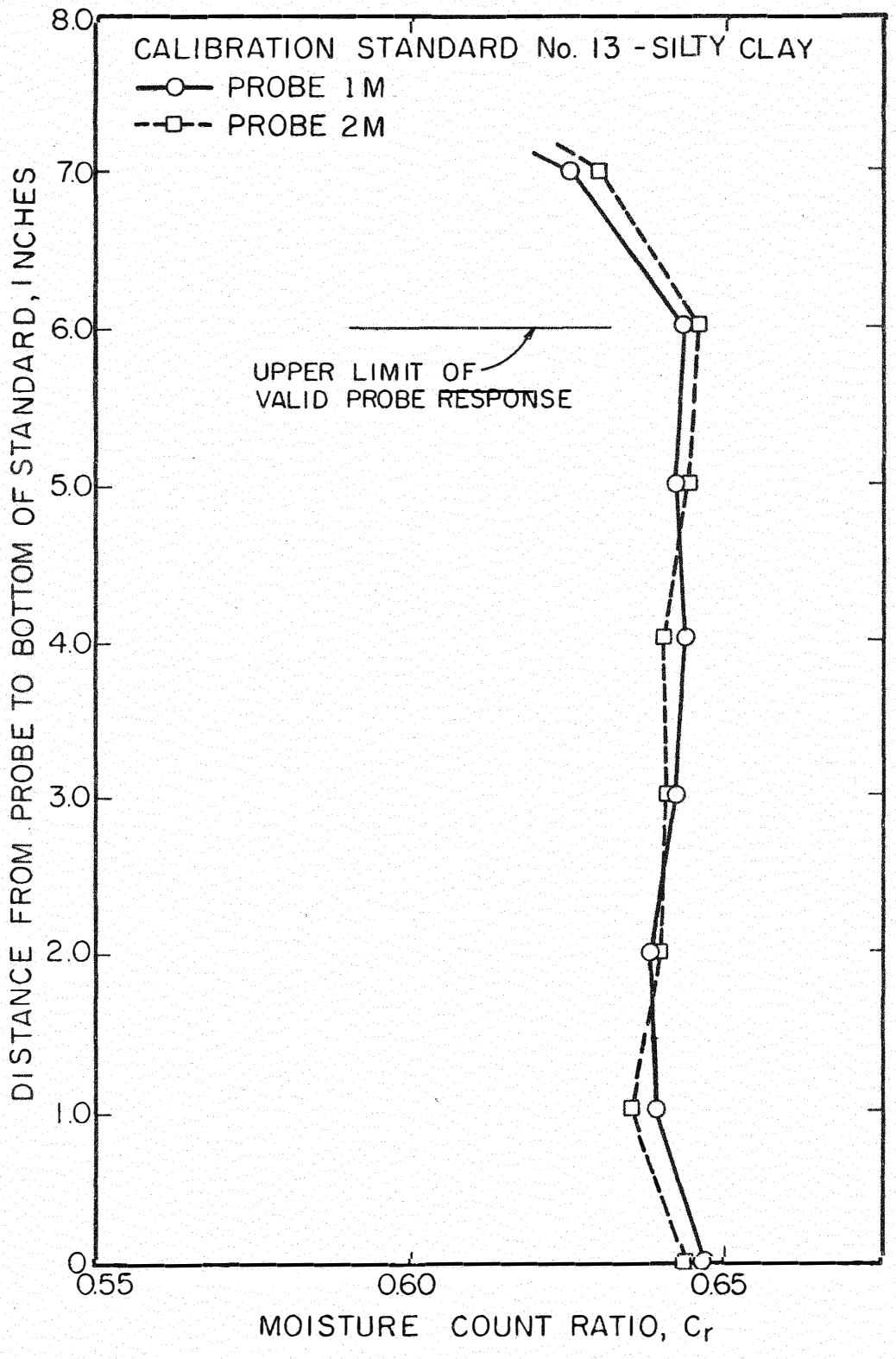


Figure 4.21. Typical Moisture Probe Response

this level.

The moisture response indicated a uniform distribution of moisture in the clay standards with a gradual decrease in count ratio as the probe was raised. This decrease is due to container geometry as the detector tube was at or near the soil surface.

In both cases, the physical dimensions of the standards limit the region of valid probe response to about six inches. The data obtained with probe at the bottom of the access tube were utilized because they differed only slightly from probe response in levels immediately above it. Data obtained in the regions discussed previously as giving erroneous pulse counts were not considered. The moisture probe data were judged valid until the response began to decrease characteristically.

It should be noted that a six-inch interval of valid response does not mean that only a six-inch segment of the standard was measured. The probes have an effective measuring length of about 14-15 inches, determining the average (integrated) moisture or density over this zone. Thus by raising the probes about six inches (in one-inch increments) from their position at the standard bottom, the entire standard was measured. Under the conditions of nuclear measurement exact values at a particular level do not have much meaning. It would appear that average values measured over some interval are more important for practical calibration purposes. Actually, it might be better to have more than 21 inches of compacted thickness and allow a larger number of nuclear measurements inside the standard. Therefore, it is recommended that future soil standards be designed with 24 to 30 inch soil thicknesses to increase the region of valid probe response. The nuclear equipment used in the study is illustrated in Figs 4.22 and 4.23.

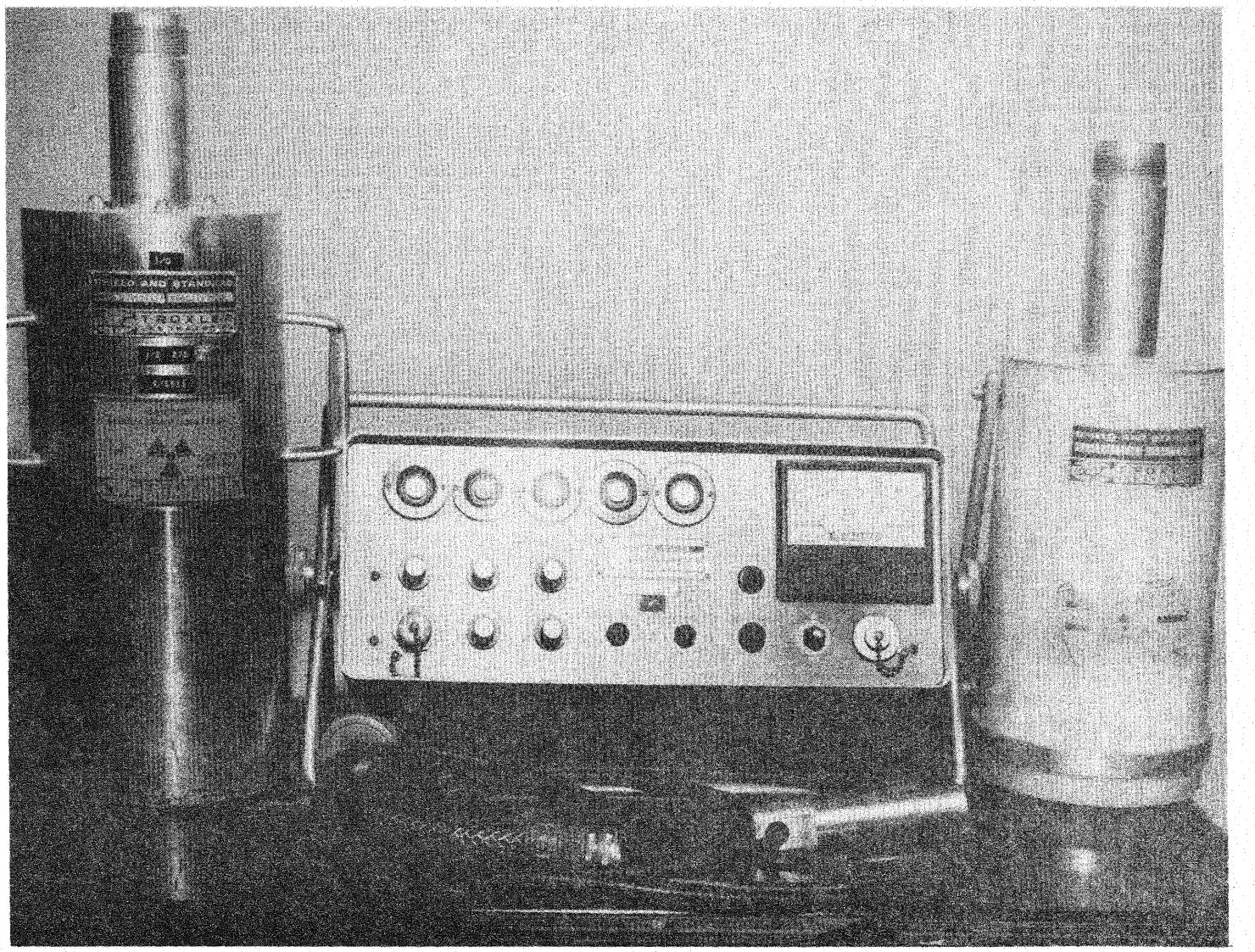


Figure 4.22. Nuclear Equipment

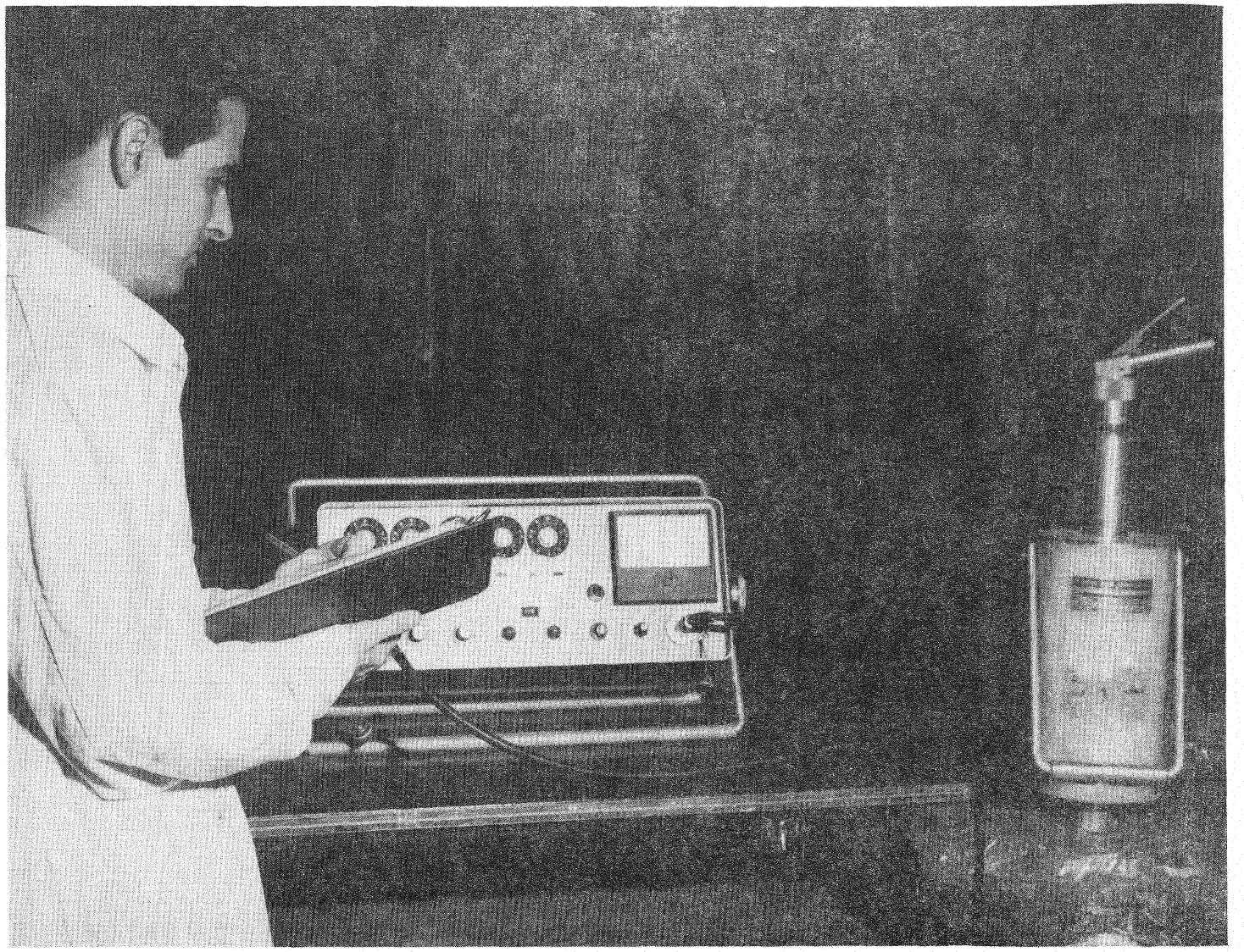


Figure 4.23. Data Collection Procedure

CHAPTER 5. DATA PRESENTATION AND EVALUATION

This chapter correlates nuclear equipment response to moisture contents and bulk densities of the calibration standards. Calibration curves for research project density and moisture probes are recommended on the basis of data obtained in this study and in previous work done at Oklahoma State University.

Nuclear Equipment Utilized

As mentioned previously, nuclear equipment manufactured by Troxler Electronic Laboratories, Inc., Raleigh, North Carolina was used in this study. Two complete sets of equipment were calibrated, each consisting of a Model 200B scaler, a Model 104 depth moisture probe with combination shield/standard, and a Model 504 depth density probe with combination shield/standard. One set of equipment was purchased in November, 1964, the other set in August, 1967. Pertinent data concerning the probes are summarized as follows:

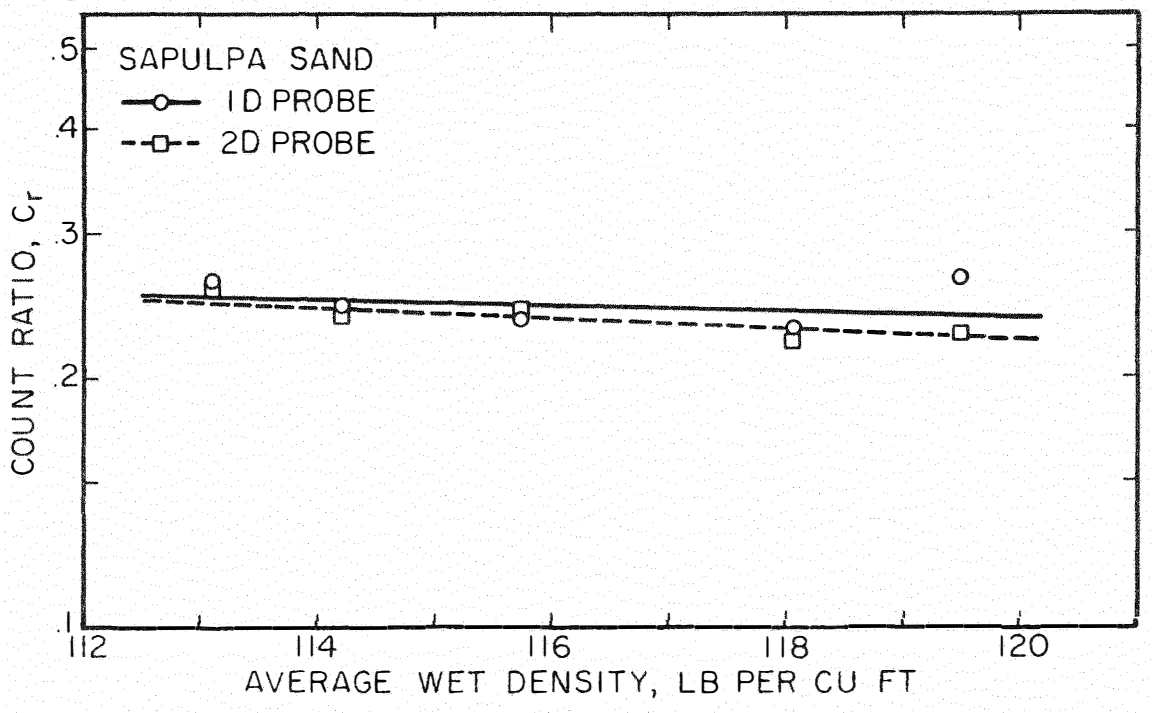
Troxler Model	Probe Type	Source	Date Purchased	Probe No.
104	Depth Moisture	3mc $Ra^{226}_{226}Be$	Nov. 1964	1M
504	Depth Density	3mc Ra^{226}_{226}	Nov. 1964	1D
104	Depth Moisture	3mc $Ra^{226}_{226}Be$	Aug. 1967	2M
504	Depth Density	3mc Ra^{226}	Aug. 1967	2D

Detailed equipment descriptions are given in Appendix 1. The "Probe No." will be used to differentiate between plotted results for each probe.

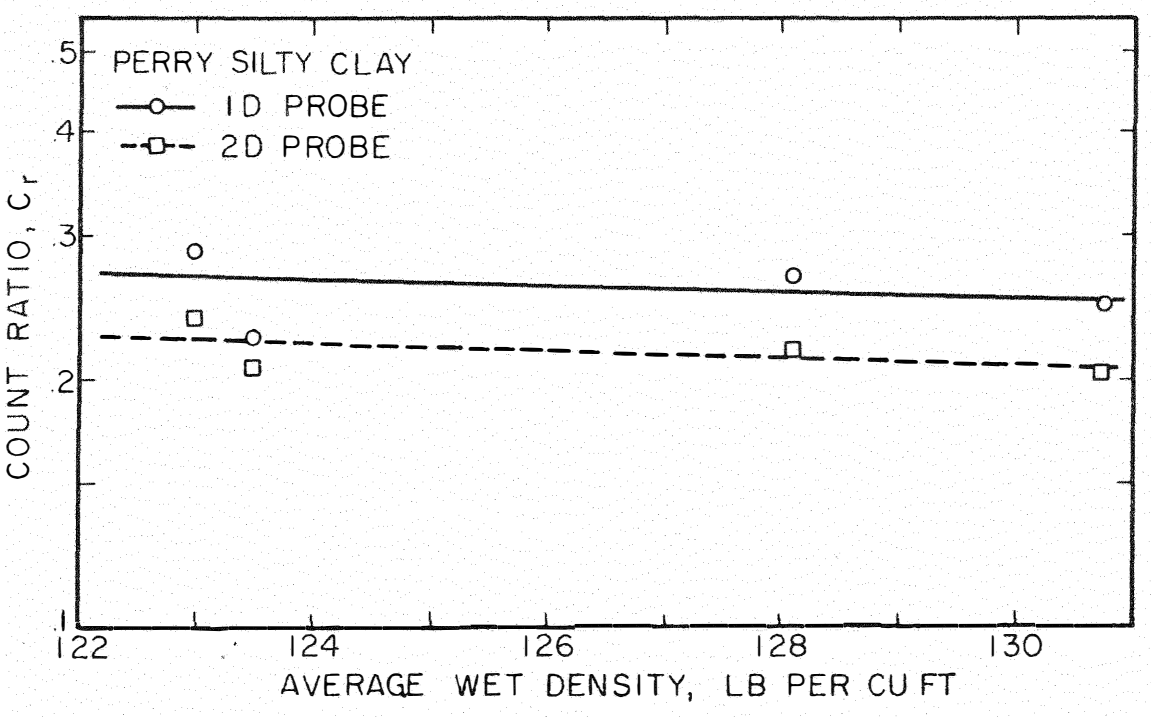
Evaluation of Density Probe Data

According to most accepted operational theories for a depth density probe of the type utilized in this study, the relationship between mass density and count ratio C_r is approximately linear on a semi-logrithmic plot, at least for values in the range of normal soil mass densities. Density data obtained in this study have thus been plotted with average count ratio as the ordinate on the log scale and average wet or bulk density in lb per cu ft as the abscissa on the arithmetic scale. A least-squares regression analysis was used to determine the linear curve equation for each set of data points. As each soil type produced only four to five data points the authors doubt if accuracy achieved with a least-squares fit is much better than could be obtained with a straight-edge and pencil. However, they must admit the former method is more "scientific".

Figure 5.1a shows calibration curves obtained from the sand standards. Despite density profiles in the sand, caused by downward moisture migration, the average nuclear response produced a good linear fit when plotted against average bulk density. For all practical purposes there is no difference in the response produced by either the 1D or 2D probes. Complete readings with both probes were taken over about a three-day interval. This was also the case for the silty clay and Permian red clay calibration standards. The sand density point at 119.50 lb per cu ft (Standard No. 2) appears to be a little high in terms of nuclear response, and this is probably the case. As mentioned previously, an attempt to remove sand from the cored hole with an auger section was made prior to inserting the access tube in the standard. The attempt, while it did remove the sand, also enlarged the diameter of the cored



a) Calibration Results for Sapulpa Sand



b) Calibration Results for Perry Silty Clay

Figure 5.1. Density Calibration Results for Sapulpa Sand and Perry Silty Clay

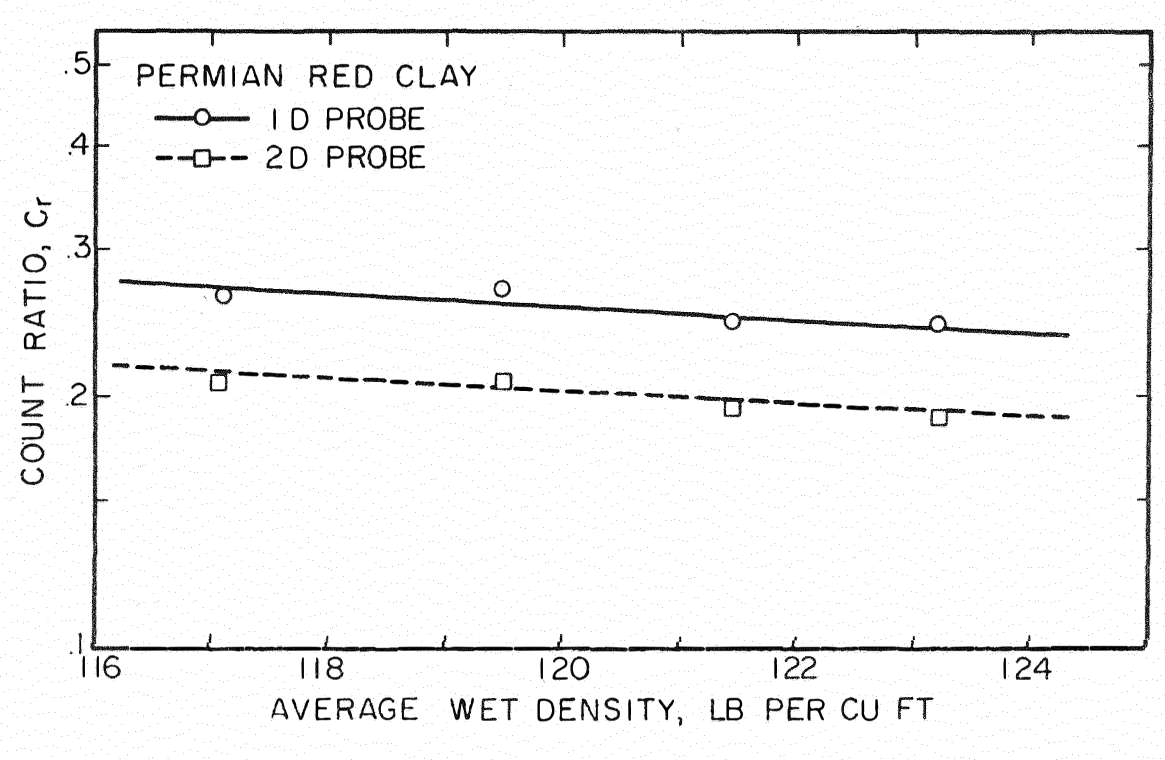
hole. With an artificially produced gap around the access tube the nuclear probes measured a slightly lower density (with a higher C_r) than that measured by bulk density weight calculations. In any case the difference was not too large, and the point was included for regression analysis.

Results for the silty clay are shown in Fig 5.1b. Again the linear theory fits experimental data points reasonably well, but it is seen that two distinct response curves exist for the two probes. The small difference between 1D and 2D probe response in sand (Fig 5.1a) has been magnified by the change in soil type. Slopes of the two curves are almost identical, but intercepts are different.

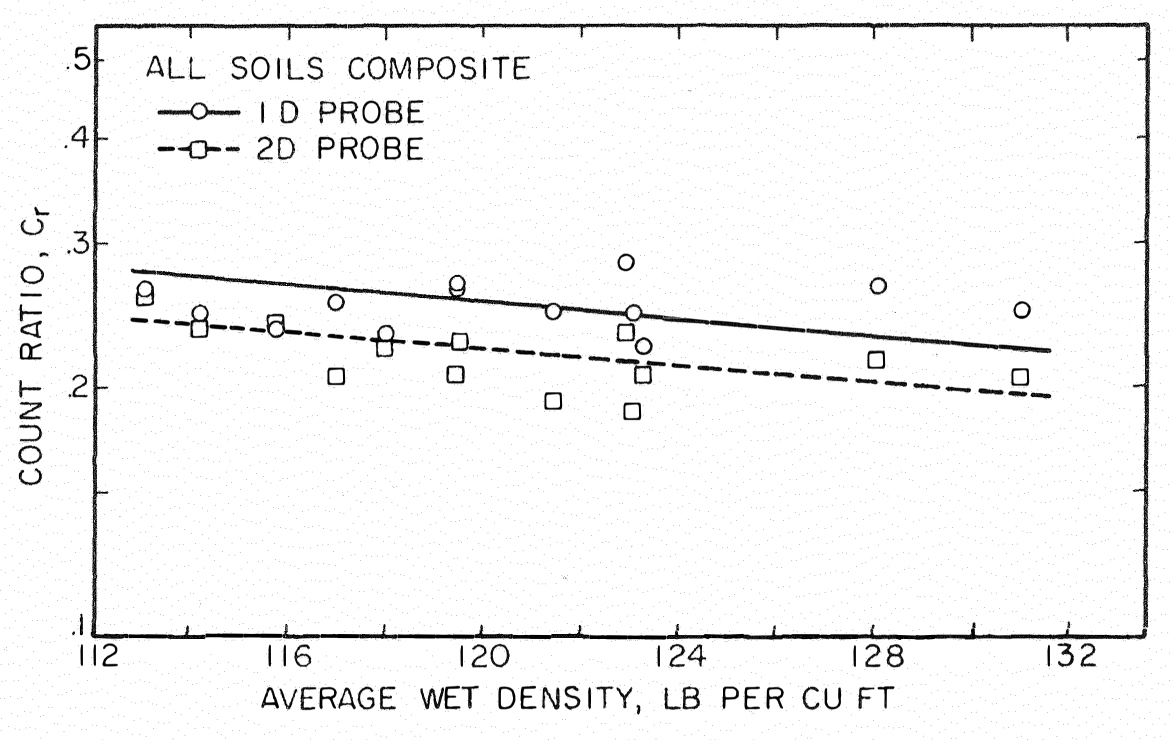
Figure 5.2a shows results for the Permian red clay calibration standards. Again the linear fit is good but two distinct curves exist for the two probes. The spread is larger than for the silty clay of Fig 5.1b. The spread between linear regressions for the 1D and 2D probes increases from sand through silty clay to Permian red clay. Interestingly enough, the degree of spread also follows the plasticity properties of the soil--from non-plastic through moderately plastic to highly plastic.

The two depth density probes and reference standards are the same model, with a three-year difference in age, and the probes appear to have similar geometry characteristics. It was initially theorized that the C_r response for both probes should be identical. Such was not the case, however, and the factory calibration curves for the two probes were also different.

Even though results of experimental measurement indicated that separate calibration curves existed for each soil type, practical



a) Calibration Results for Permian Red Clay



b) Calibration Results for All Soils Tested

Figure 5.2. Density Calibration Results for Permian Red Clay and for All Soils

engineering considerations required that some single curve be developed for evaluating data from the large number of field test sites installed to measure subgrade moisture variations. The variety of soil types existing at the different field test sites and the variability of soil type at particular sites made the use of separate calibration curves for each of many soils unrealistic. Initial choice of calibration media recognized this fact as the sand, silty clay, and Permian red clay were selected because they were good examples of typical non-plastic, moderately plastic, and highly plastic soils encountered in field work.

The spread between 1D and 2D probe response caused by the two plastic soils was considered by making two separate "all soils composite" calibration curves, shown in Fig 5.2b. The linear regression equations for these two curves, given in Table 5.1 (along with the equations for other density curves and for moisture curves discussed in the next section) have been selected for use in reducing all research project nuclear density data. While the chosen solution may not be acceptable from a purely scientific point of view, it appears to be a reasonable engineering compromise.

As a matter of interest, the "all soils composite" curves for the two depth density probes were plotted against factory calibration curves for the probes. As mentioned previously, Troxler Electronic Laboratories, Inc., calibrated the probes in portland cement concrete standards. Results of the comparison are shown in Fig 5.3a for the 1D probe and Fig 5.3b for the 2D probe. The "all soils composite" curve for each is very close to the respective factory calibration curve for each probe. While the individual soils produced different curves their average was almost the same as a curve produced by calibration in port-

DENSITY CALIBRATION RESULTS

Calibration Media	Probe	Regression Equation
Sapulpa Sand	1D	Log % Std. = 1.71399 - .00278D*
Sapulpa Sand	2D	Log % Std. = 1.91997 - .00466D
Perry Silty Clay	1D	Log % Std. = 1.83068 - .00327D
Perry Silty Clay	2D	Log % Std. = 1.94090 - .00485D
Permian Red Clay	1D	Log % Std. = 2.23835 - .00690D
Permian Red Clay	2D	Log % Std. = 2.30150 - .00837D
All Soils Composite	1D	Log % Std. = 2.08842 - .00579D
All Soils Composite	2D	Log % Std. = 1.92682 - .00489D
Troxler Factory (Concrete)	1D	Log % Std. = 2.17815 - .00650D
Troxler Factory (Concrete)	2D	Log % Std. = 2.14331 - .00652D
LeFevre-Manke	1D	Log % Std. = 2.08490 - .00570D

MOISTURE CALIBRATION RESULTS

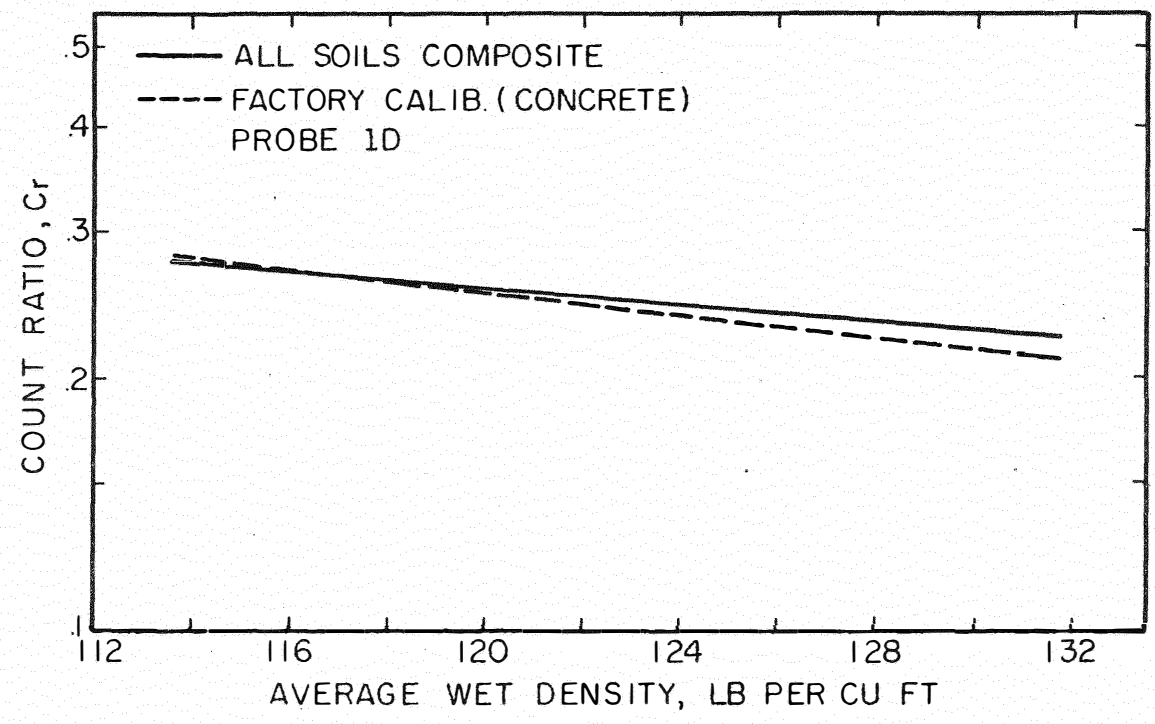
Calibration Media	Probe	Regression Equation
Sapulpa Sand w/o No. 2	1M	% Std. = 26.47 + 2.93W**
Sapulpa Sand w/o No. 2	2M	% Std. = 22.94 + 3.14W
Perry Silty Clay	1M	% Std. = 9.37 + 3.21W
Perry Silty Clay	2M	% Std. = 11.24 + 3.16W
Permian Red Clay	1M	% Std. = 20.16 + 2.80W
Permian Red Clay	2M	% Std. = 13.82 + 3.22W
Sapulpa Sand w/o No. 2	1M & 2M	% Std. = 24.70 + 3.04W
Perry Silty Clay	1M & 2M	% Std. = 10.30 + 3.24W
Permian Red Clay	1M & 2M	% Std. = 16.99 + 3.01W
PRC-SC Composite	1M & 2M	% Std. = 13.65 + 3.10W
Troxler Factory	1M	% Std. = 6.69 + 3.43W
Troxler Factory	2M	% Std. = 5.50 + 1.95W

* D = Wet Density in lb per cu ft

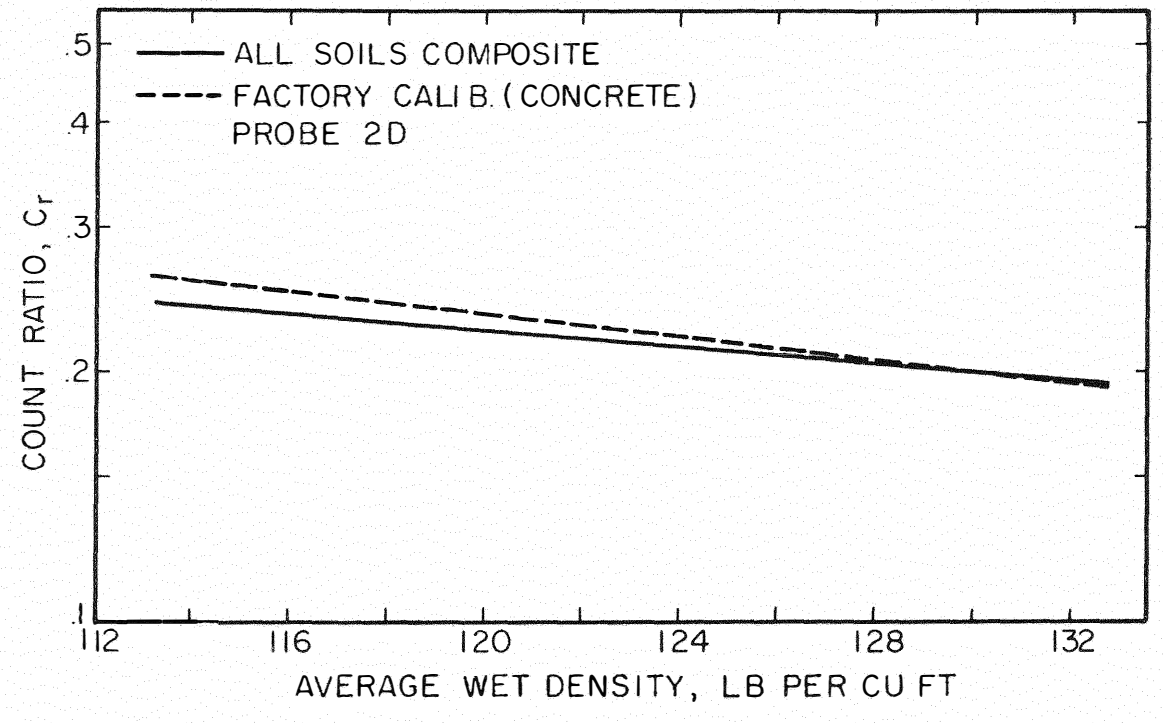
** W = volumetric water content in lb per cu ft

Note: $C_r = \frac{\%\ \text{Std.}}{100}$

Table 5.1 Calibration Curve Equations



a) Calibration Results for Probe 1D



b) Calibration Results for Probe 2D

Figure 5.3. Comparison of Soil Composite and Factory Density Calibration Curves

land cement concrete standards. The authors believe this to be coincidence, as accepted theories of backscatter depth probe operation indicate that different response curves should exist for different calibration media. However, they must admit (somewhat against their will) that, for this case, the factory concrete calibration curves are about as nearly accurate as their "all soils composites" for practical engineering purposes in Oklahoma.

LeFevre and Manke (Ref 3), in previous work at Oklahoma State University with the 1D probe, suggested a "band-width" type calibration, based on work with primarily coarse-grained soil materials (aggregates). As can be seen from Fig 5.4, the "all soils composite" curve for the 1D probe, developed from fine-grained soils, falls in the center of their proposed band. The regression equation for the center of their proposed band is also given in Table 5.1. Thus LeFevre and Manke's proposed band idea has been further validated by work with fine-grained soils -- the use of an "all soils composite" curve is a similar approach.

Evaluation of Moisture Probe Data

According to most accepted theories for a depth moisture probe of correct geometric configuration, the relationship between volumetric water content and count ratio C_r is approximately linear on an arithmetic plot, at least for the range of water contents normally found in soils. This relationship naturally assumes all significant hydrogen in the soil occurs in water form. Accordingly, moisture values obtained in this study have been plotted with average count ratio C_r as the ordinate and average volumetric water content in lb per cu ft as the abscissa. Linear regression curves were calculated for each set of data points.

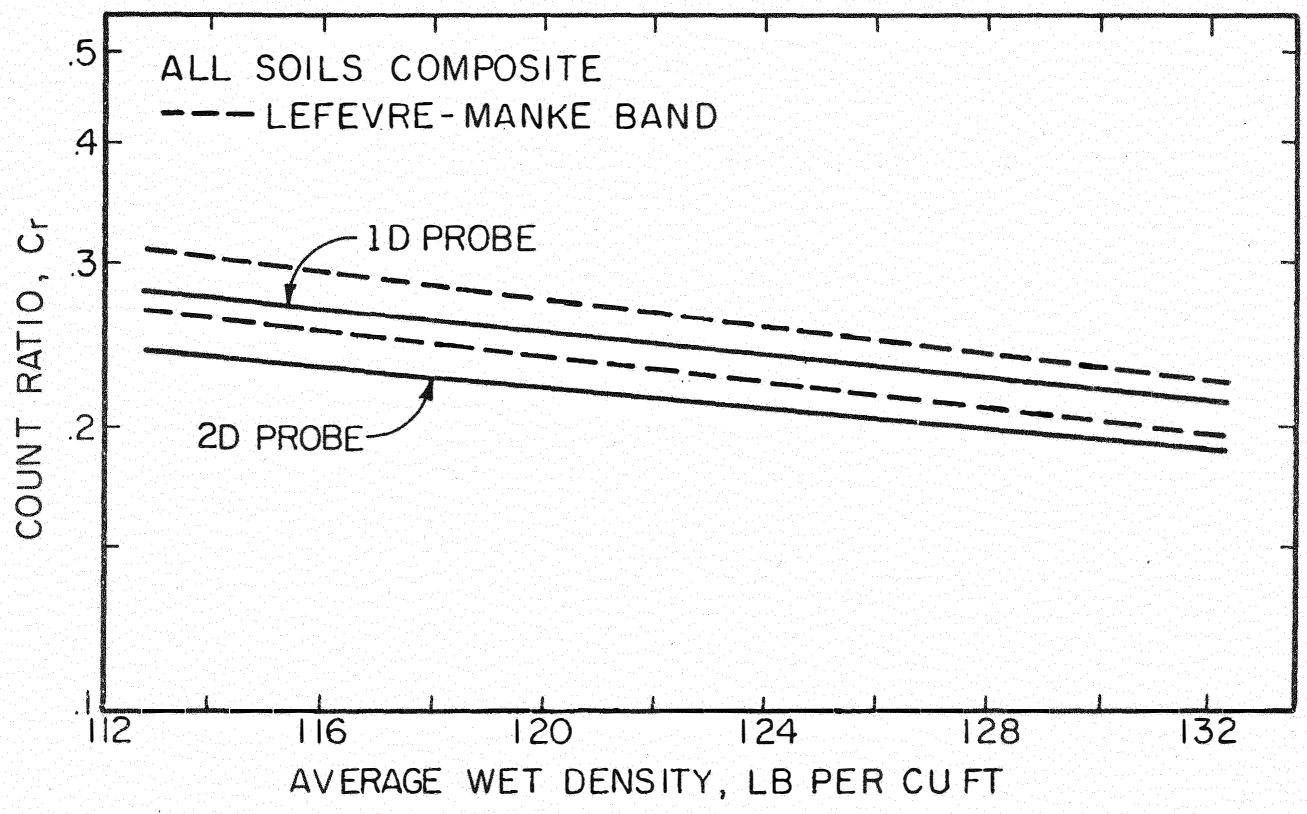


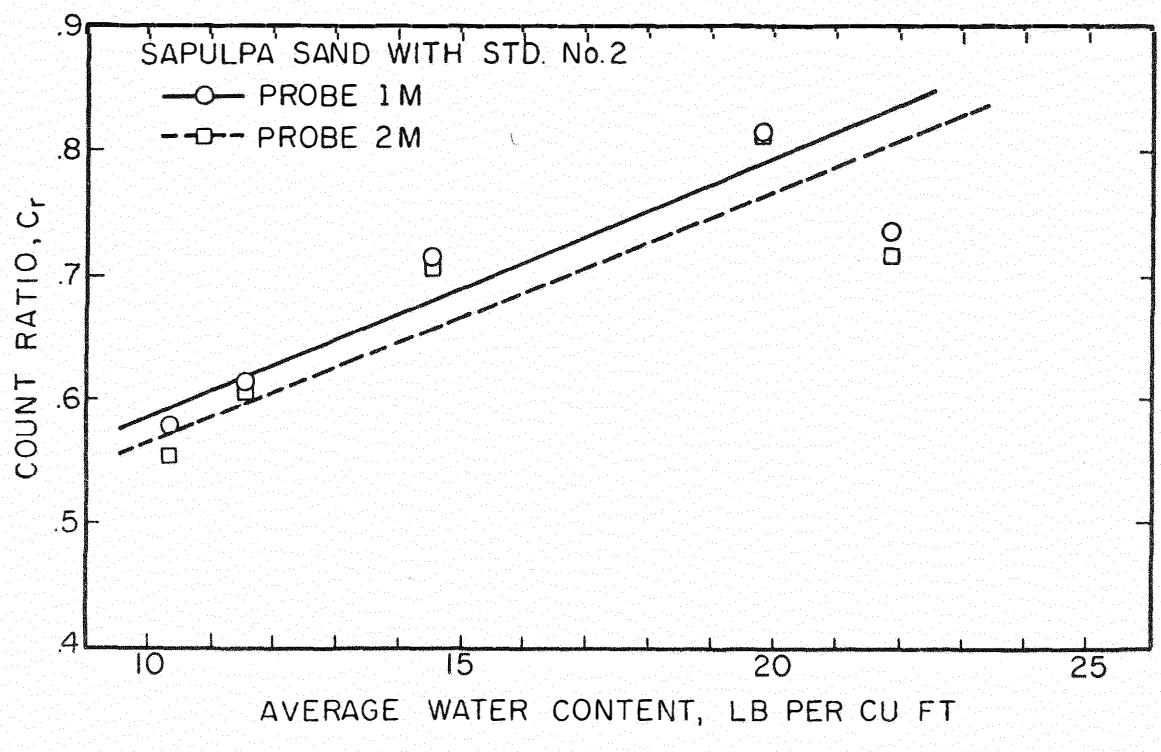
Figure 5.4 Comparison of Soil Composite Curves to LeFevre and Manke Band

Results of calibration in the sand standards are shown in Fig 5.5a. Despite the known moisture profile in the sand standards, a reasonable linear fit is obtained with the exception of the point at 21.89 lb per cu ft water content (Standard No. 2). As mentioned previously, difficulties with this Standard resulted in a large gap around the access tube. The data point was assumed to be in error, and linear curves were recalculated without it, as shown in Fig 5.5b. A better linear fit was obtained, and for all practical purposes there is no difference between response of the two moisture probes.

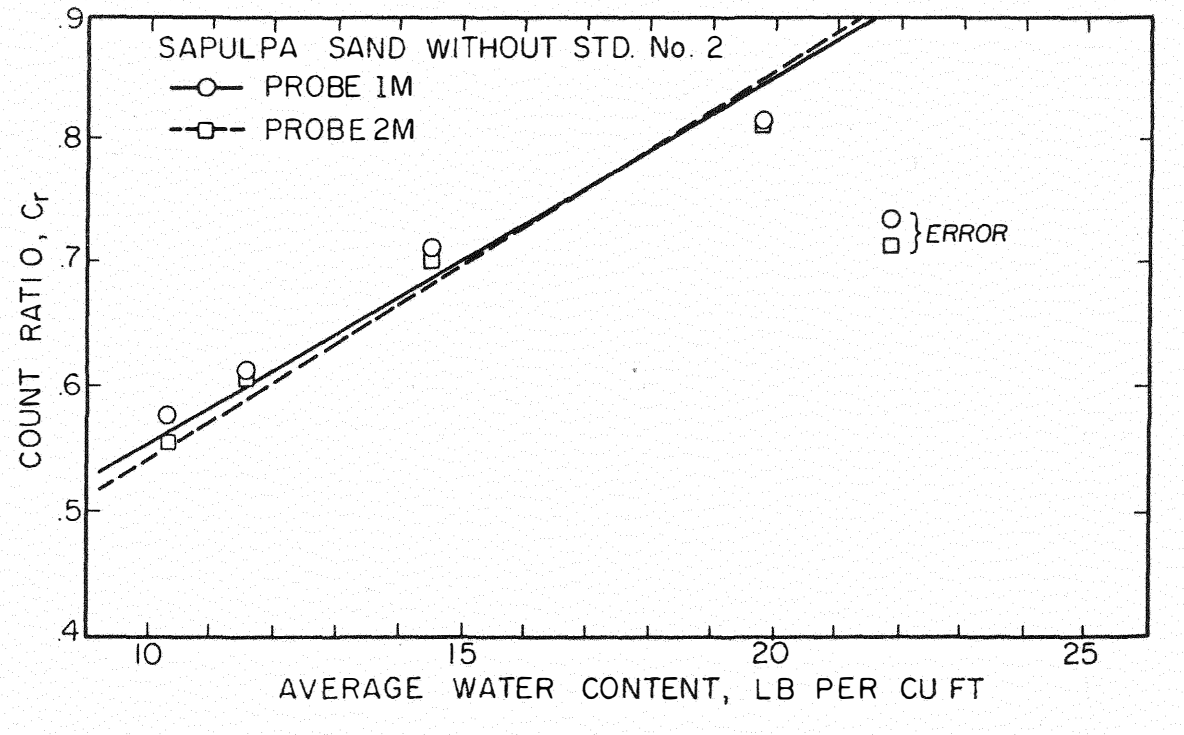
Figure 5.6a shows plotted results for the silty clay. Again a reasonable linear fit is obtained, and there is little spread between the 1M and 2M curves. The Standard giving a data point at 9.44 lb per cu ft water content was compacted to have a moisture probe sphere of influence extending outside the container, as predicted by Eq 3.1. However, the data point appears valid, and was included in regression analysis. Perhaps Eq 3.1 is slightly conservative.

Good linear fits are seen in Fig 5.6b for the Permian red clay. In contrast to the spread between 1D and 2D density probe response, which increased with increasing plasticity, for all practical purposes the 1M and 2M probes give identical C_r readings in each soil type.

This similar behavior makes it feasable to construct a composite or median curve for both probes in each soil type. The three composites are shown in Fig 5.7 and indicate that each soil type has a distinct response curve. As was found for the density probe, all curves have about the same slope but different intercepts. If the procedure used for density probes was followed, then the three individual curves for sand, silty clay, and Permian red clay should be combined into an "all

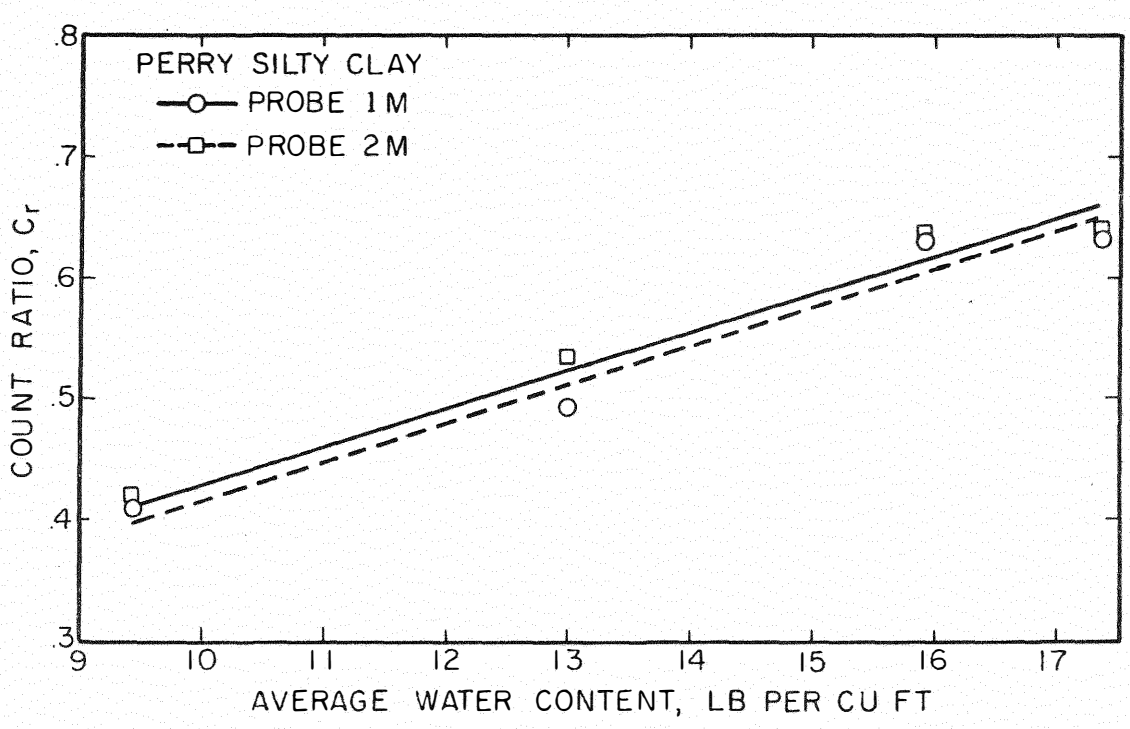


a) Calibration Results with Standard No. 2

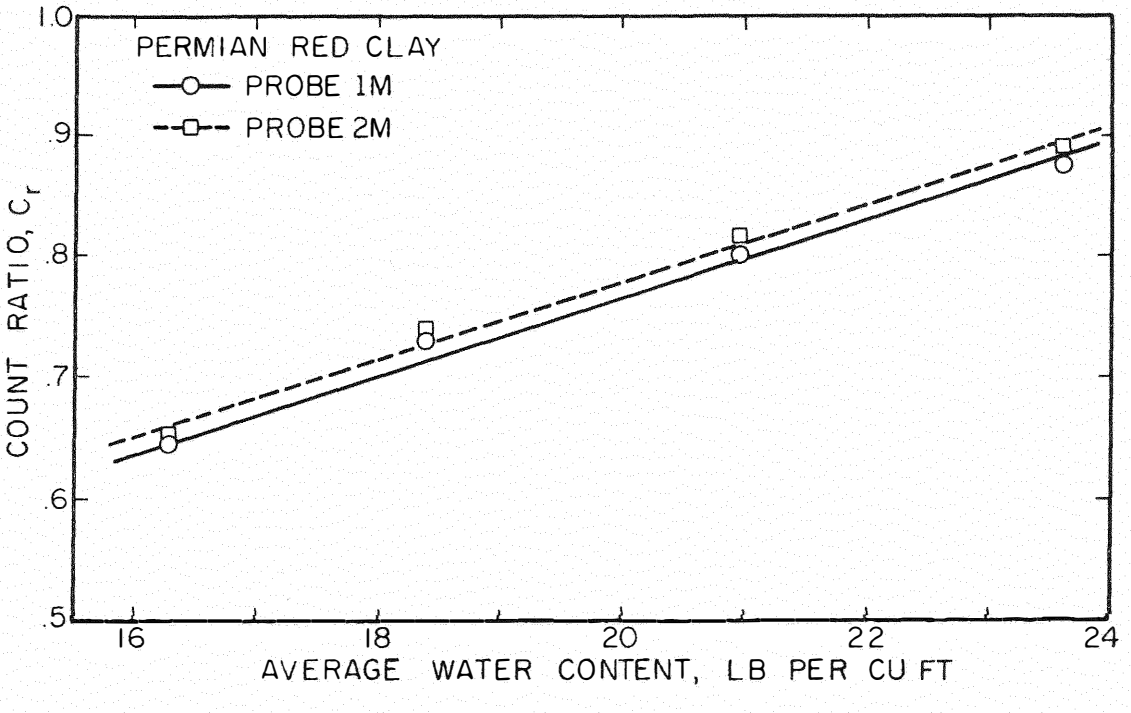


b) Calibration Results without Standard No. 2

Figure 5.5. Moisture Calibration Results for Sapulpa Sand



a) Calibration Results for Perry Silty Clay



b) Calibration Results for Permian Red Clay

Figure 5.6. Moisture Calibration Results for Perry Silty Clay and Permian Red Clay

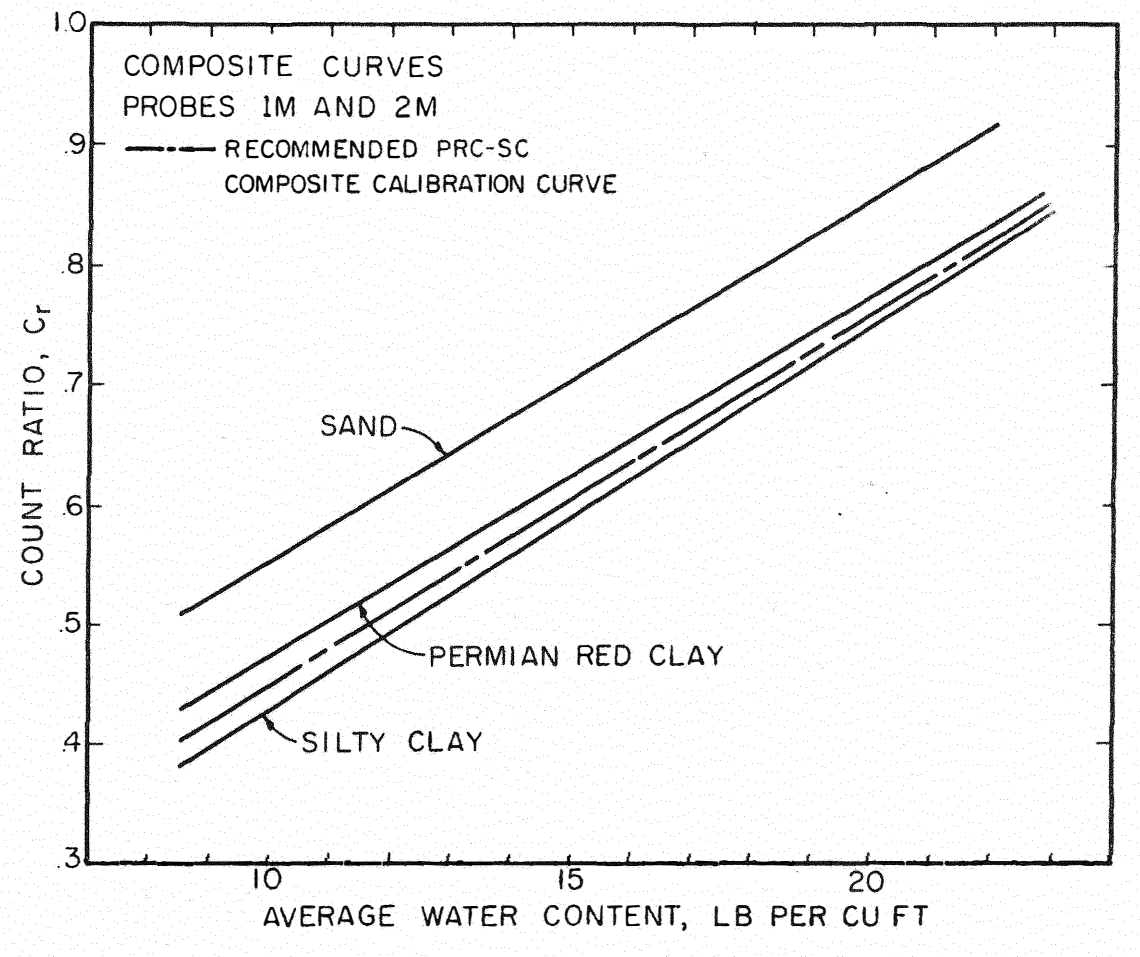


Figure 5.7 Comparison of Moisture Calibration Results for All Soils

soils composite" and this curve used for reduction of field data.

However, inspection of Fig 5.7 reveals that the curves for the plastic soils, silty clay and Permian red clay, are relatively close while the curve for the non-plastic sand lies above them. As more nearly accurate values of absolute moisture content are of greater importance in determining engineering behavior of cohesive soils than sands, it was decided to combine the Permian red clay and silty clay data and develop a more nearly accurate composite moisture calibration curve for use in cohesive soils. As all the soil curves have about the same slope, moisture changes in cohesionless material should still be recorded correctly. This curve, indicated as "PRC-SC Composite" in Fig 5.7, was selected for reduction of research project moisture data from both the 1M and 2M probes.

Figure 5.8 shows the "PRC-SC Composite" curve along with factory calibration curves for the two moisture probes. As mentioned previously, factory calibration was carried out in cadmium chloride solution standards, correlated to North Carolina soil moisture contents. Of interest is the fact that individual factory curves for the two probes (of the same model) differ greatly, while the authors' experimental work indicated almost identical response characteristics. The 1M factory curve is close to the composite recommended for project use but the 2M curve is not. Also shown in Fig 5.8 is a calibration curve recommended by LeFevre and Manke (Ref 3) for the 1M probe. This curve has a steeper slope than any of the others; however, LeFevre and Manke worked primarily with coarse-grained material (aggregates) in saturated and drained states. Their construction of aggregate standards by compacting aggregate around the probe access tube may have caused excess pore space adjacent to the tube. When saturated, these standards would exhibit a higher moisture

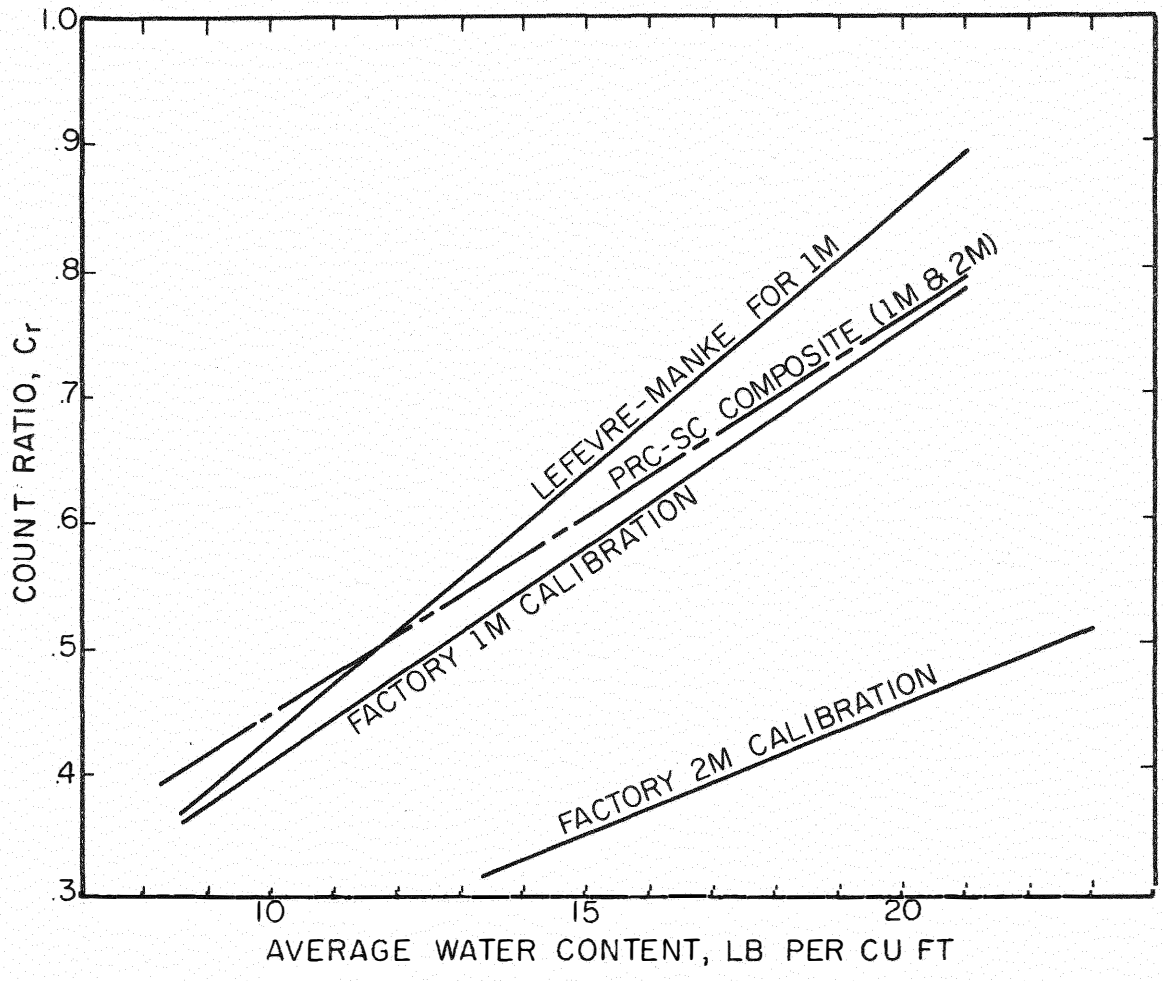


Figure 5.8. Comparison of Soil Composite and Factory Moisture Calibration Curves

probe C_r than might be expected from average water content calculations.

Summary

Experimental data for all soil calibration standards are summarized in Table 5.2. The use of "dual-purpose" standards to calibrate both nuclear depth moisture and density probes has produced mixed results. Reasonable fits have been obtained from experimental data and the use of dual-purpose soil calibration standards has been validated, at least over the range of measurement useful in soils/highway engineering. From a practical engineering point of view, calibration curves have been developed which should allow reasonable absolute value measurements in Oklahoma subgrades. Thus specific research project goals have been met.

However, reasons for soil type variance in nuclear probe response have not been established. Results of a comprehensive chemical analysis on all three soils (Appendix 2) failed to indicate the presence of any significant amounts of gamma or neutron absorbers. Thus the authors cannot definitely say why each soil had a different moisture response curve or why increases in soil plasticity produced increasing spread between responses of two similar depth density probes. All differences certainly appear to be soil type effects and not experimental errors. Current OSU research to attempt application of Gardner and Roberts' mathematical models for surface gages (Ref 18) to depth probe use may give some insight into soil type effects. Continued experimental research to determine if nuclear response is influenced significantly by each individual soil or only by general classes of soils is also planned if time and funds permit.

Most of the calibration difficulties can be traced to the rather

Calibration Standard No.	Calibration Material	Design Criteria	γ_{wet} (pcf)	γ_{dry} (pcf)	$\bar{w}$ (%)	Volumetric Moisture Content (pcf)	Average C_r Moisture 1M	Average C_r Moisture 2M	Average C_r Density 1D	Average C_r Density 2D
1	Sand	e=0.67 w=20%	119.50	107.10	11.58	12.40	.614	.609	.269	.238
2	Sand	e=0.67 w=25%	118.09	96.20	22.75	21.89	.786	.764	.239	.226
3	Sand	e=0.67 w=22%	114.21	99.73	14.52	14.48	.715	.716	.248	.235
4	Sand	e=0.67 w-18%	113.14	102.53	10.35	10.61	.571	.551	.265	.254
5	Sand	e=0.67 w=24%	115.73	96.62	19.78	19.11	.817	.818	.239	.244
6	PRC	γ_d=117 w=16%	123.15	106.83	15.28	16.32	.646	.655	.243	.186
7	PRC	γ_d=110 w=19%	119.54	101.15	18.18	18.39	.729	.741	.271	.209
8	PRC	γ_d=103 w=22%	121.44	100.41	20.94	21.03	.801	.821	.249	.190
9	PRC	γ_d=96 w=25%	117.09	93.47	25.27	23.62	.853	.890	.263	.204
10	Silty Clay	γ_d=119 w=9%	123.54	114.10	8.27	9.44	.401	.405	.224	.205
11	Silty Clay	γ_d=112 w=12%	130.72	117.71	11.05	13.00	.495	.504	.243	.199
12	Silty Clay	γ_d=106 w=15%	128.08	112.11	14.24	15.96	.631	.634	.260	.215
13	Silty Clay	γ_d=100 w=18%	123.00	105.59	16.49	17.41	.636	.639	.281	.233

Table 5.2. Data Summary Sheet

flat slope of the depth density probe response curve. Only small difference in count ratio occur with large changes in wet density. Perhaps sensitivity could be increased by lengthening the probe, and thus the distance between source and detector, but one would then have even more trouble using wet density and volumetric moisture readings at the "same level" to compute dry density and engineering moisture content. It should be noted, however, that the procedure used to compute engineering results from nuclear data tends to minimize (or at least lessen the effect of) faulty depth density probe calibration. In the normal range of soil densities and water contents, a large 10% error in wet density will produce only about a 4% error in engineering moisture content.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

A procedure for calibration of nuclear depth moisture and density probes has been described in the preceding chapters. Experimental data have been plotted and evaluated. Based on results obtained, the following conclusions may be drawn:

1. The use of dual-purpose actual soil calibration standards has been validated. With a little care and equipment available in most general materials laboratories the effect of soil type on nuclear probe response may be determined, at least for the range of measurement useful in soils/highway engineering.
2. For practical engineering use of the probes in Oklahoma subgrades, median/composite calibration curves for nuclear depth moisture and density probes appear satisfactory.
3. Nuclear depth density probe response was affected by type of soil calibration media. Furthermore, response differences between two probes of the same model increased with increasing soil plasticity.
4. Nuclear depth moisture probe response was also affected by type of soil calibration media. However, almost identical responses were obtained in each soil with two probes of the same model despite a large difference in factory calibration curves for the probes.
5. No significant amount of either gamma or neutron absorbing elements was found to exist in the calibration soils.

6. No definite reasons for the effect of soil type on nuclear response, other than those cited in referenced literature, are given at this time.

Further research is indicated by results obtained to date. While practical engineering solutions have been obtained for a specific problen, widespread civil engineering use of nuclear depth probes cannot become a reality until several basic questions are resolved. Thus,

1. A wider range of soils should be studied, to determine if most soil type effects are caused by individual soils or by broad classes or types of soils.
2. Attention should be given to correlation of physical, mineral, and chemical properties with nuclear probe response. Particular emphasis should be given to correlating the results from standard engineering tests. Chemical property and "mathematical model" correlation attempts may help to give insight into basic problems, but their acceptance by field engineers may be slow.
3. The processing phase of cohesive soil calibration standard preparation is the most time-consuming part of the process. This procedure should be made more efficient, if possible.

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APPENDIX 1

NUCLEAR EQUIPMENT

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NUCLEAR EQUIPMENT

SET PURCHASED NOVEMBER 1964

1. Scaler: Troxler Model 200-B, Serial 256; Project No. 1S.
2. Density Equipment: Troxler Model 504 Depth Density Probe, Serial 23, using a 3mc Ra^{226} Source, Serial R-3-15; Troxler Model S-7 Shield and Standard, Serial 77; Project No. 1D.
3. Moisture Equipment: Troxler Model 104 Depth Moisture Probe, Serial G-19953, using a 3mc Ra^{226}—Be Source, Serial N-3-149; Troxler Model S-5 Shield and Standard, Serial 407; Project No. 1M.

SET PURCHASED AUGUST 1967

1. Scaler: Troxler Model 200B, Serial 525-C; Project No. 2S.
2. Density Equipment: Troxler Model 504 Depth Density Probe, Serial 21, using a 3mc Ra^{226} Source, Serial R-3-50; Troxler Model S-7 Shield and Standard, Serial 79; Project No. 2D.
3. Moisture Equipment: Troxler Model 104 Depth Moisture Probe, Serial G-22122, using a 3mc Ra^{226} Be Source, Serial 435; Project No. 2M.

APPENDIX 2

RESULTS OF CHEMICAL ANALYSIS ON CALIBRATION SOILS

APPENDIX 2

RESULTS OF CHEMICAL ANALYSIS ON CALIBRATION SOILS

Element/Compound	Percentage of Composition		
	Sand	Silty Clay	Permian Red Clay
Beryllium	*	*	*
Boron	.005-.05%	**	**
Cadmium	*	*	*
Calcium	0.086%	0.29%	0.73%
Iron	0.28%	1.37%	2.54%
Lithium	0.005%	*	0.002%
Magnesium	0.085%	0.29%	0.37%
Potassium	0.20%	0.87%	1.01%
Silicon Dioxide	77.00%	70.60%	75.40%
Sodium	0.085%	0.55%	0.58%

* Less Than 0.001%

** Less Than 0.005%